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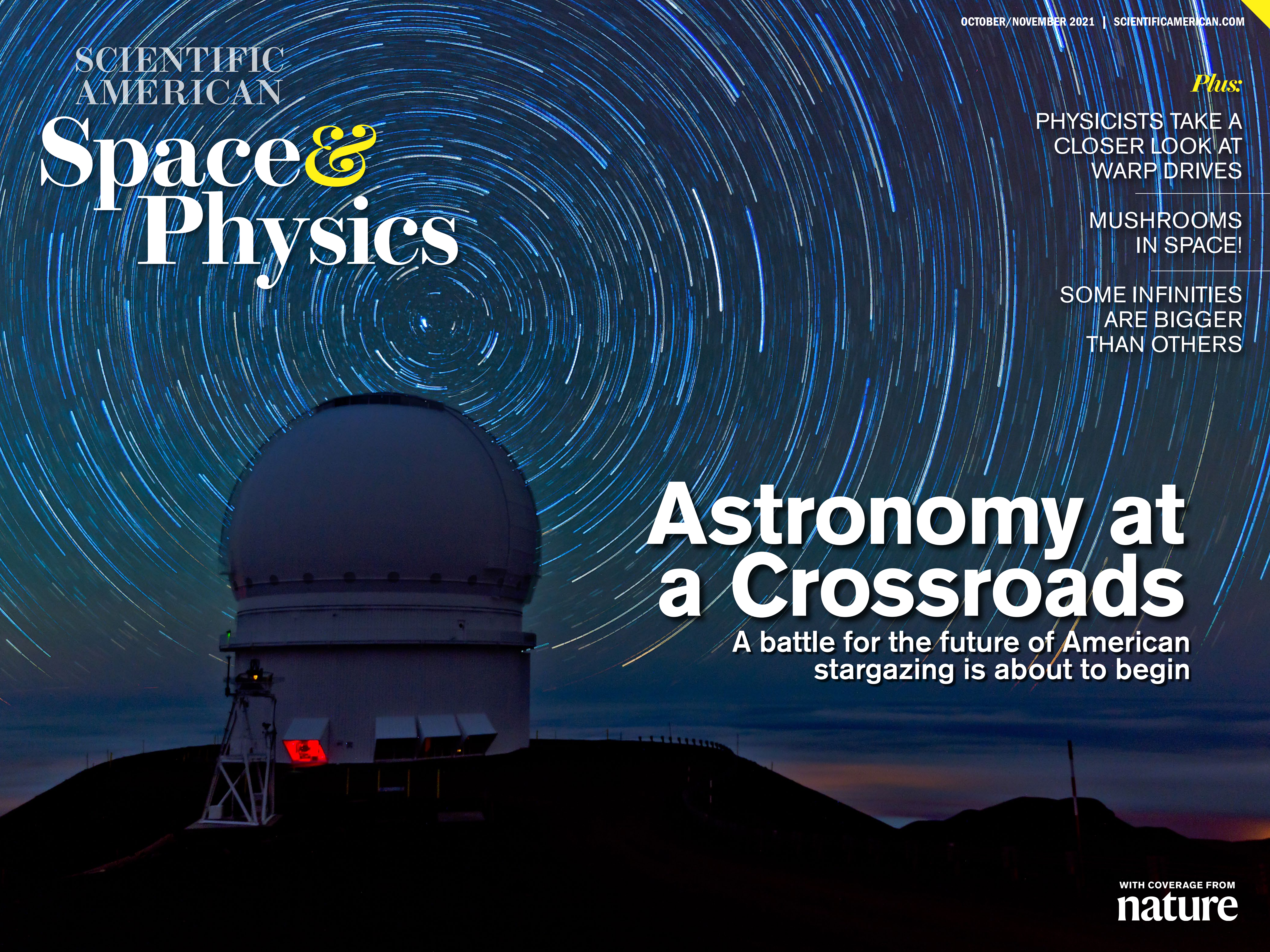

Plus:

PHYSICISTS TAKE A CLOSER LOOK AT WARP DRIVES

MUSHROOMS IN SPACE!

SOME INFINITIES ARE BIGGER THAN OTHERS

Astronomy at a Crossroads

A battle for the future of American stargazing is about to begin

WITH COVERAGE FROM nature


Liz Tormes

The Power of the Headline

When news journalists write headlines, they brainstorm the most succinct, compelling encapsulation–the take-home message–for their articles. This is much trickier than it sounds, as certain phrasings might misrepresent a story's essence or omit important elements. In this collection, senior space editor Lee Billings does an in-depth analysis of what might be included in the decadal astronomy report, set to be released any moment by the U.S. National Academies of Science, Engineering, and Medicine. It will help set the national priorities for astronomical research and budgeting for the next decade and beyond, as our article's title indicates (see "This Report Could Make or Break the Next 30 Years of U.S. Astronomy").

As I read Billings's article, I couldn't help but be reminded of headline writing. As John O'Meara, chief scientist of the W. M. Keck Observatory on Mauna Kea in Hawaii, astutely tells Billings, to get public buy-in for space funding, the decadal report would do well to come up with a single mission objective for people to rally around–"What causes life in the universe?" for example. No small feat considering the many stakeholders and interests at the table, not to mention the myriad questions astronomers are hoping to answer in the coming years. As we say in journalism, a strong headline can be what determines if anyone reads your article at all. Apparently the near future of cosmology may hinge on a winning banner statement, too. We'll soon see how well the decadal report authors do.

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On the Cover

A battle for the future of American stargazing is about to begin

WHAT'S INSIDE

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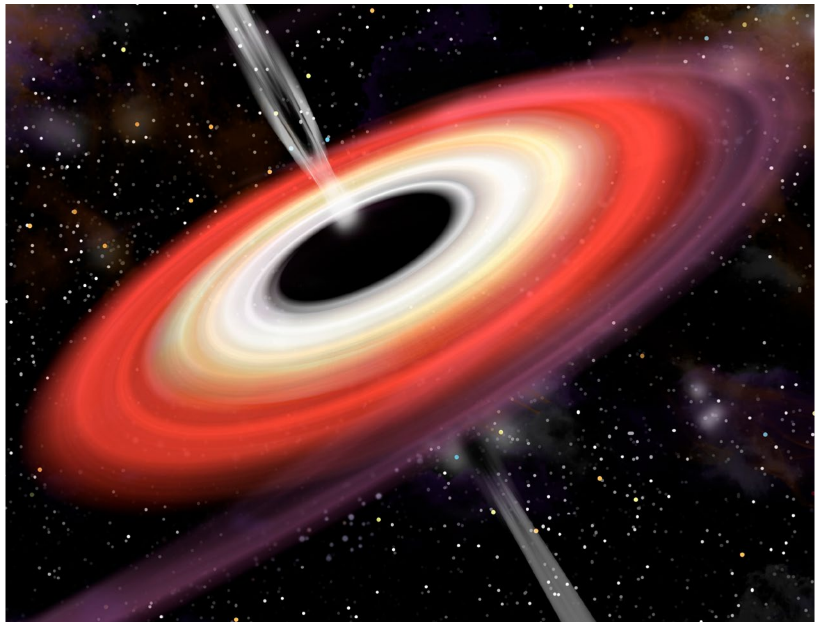

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NEWS

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OPINION

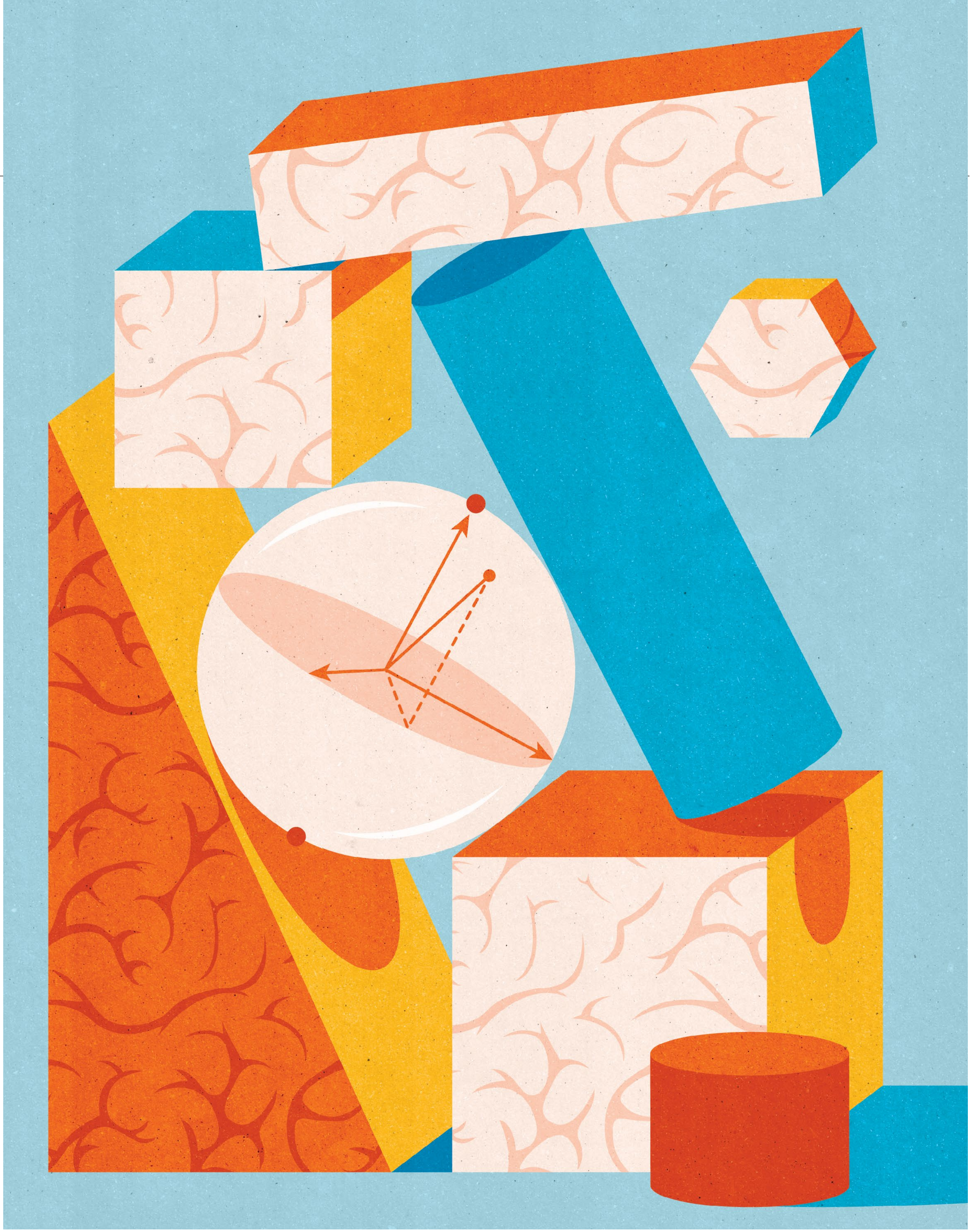
NEWS

AI Designs Quantum Physics Experiments beyond What Any Human Has Conceived

Originally built to speed up calculations, a machine-learning system is now making shocking progress at the frontiers of experimental quantum physics

Quantum physicist Mario Krenn remembers sitting in a café in Vienna in early 2016, poring over computer printouts, trying to make sense of what MELVIN had found. MELVIN was a machine-learning algorithm Krenn had built, a kind of artificial intelligence. Its job was to mix and match the building blocks of standard quantum experiments and find solutions to new problems. And it did find many interesting ones. But there was one that made no sense. “The first thing I thought was, ‘My program has a bug because the solution cannot exist,’” Krenn says.

MELVIN had seemingly solved the problem of creating highly complex entangled states involving multiple photons (entangled states being those that once made Albert Einstein invoke the specter of “spooky action at a distance”). Krenn, Anton Zeilinger of the University of Vienna and their colleagues had not explicitly provided MELVIN the rules needed to generate such complex states, yet it had found a way. Eventually Krenn realized that the algorithm had rediscovered a type of experimental arrangement that had been



Kotryna Zukauskaite

devised in the early 1990s. But those experiments had been much simpler. MELVIN had cracked a far more complex puzzle. "When we understood what was going on, we were immediately able to generalize [the solution]," says Krenn, who is now at the University of Toronto.

Since then, other teams have started performing the experiments identified by MELVIN, allowing them to test the conceptual underpinnings of quantum mechanics in new ways. Meanwhile Krenn, working with colleagues in Toronto, has refined their machine-learning algorithms. Their latest effort, an AI called THESEUS, has upped the ante: it is orders of magnitude faster than MELVIN, and humans can readily parse its output. While it would take Krenn and his colleagues days or even weeks to understand MELVIN's meanderings, they can almost immediately figure out what THESEUS is saying. "It is amazing work," says theoretical quantum physicist Renato Renner of the Institute for Theoretical Physics at the Swiss Federal Institute of Technology Zurich, who reviewed a 2020 study about THESEUS but was not directly involved in these efforts.

Krenn stumbled on this entire research program somewhat by accident when he and his colleagues were trying to figure out how to experimentally create quantum states of photons entangled in a very particular manner. When two photons interact, they become entangled, and both can be mathematically described only using a single shared quantum state. If you measure the state of one photon, the measurement instantly fixes the state of the other even if the two are kilometers apart (hence Einstein's derisive comments on entanglement being "spooky").

In 1989 three physicists—Daniel Greenberger, the late Michael Horne and Zeilinger—described an entangled state that came to be known as GHZ (after their initials). It involved four photons, each of which could be in a quantum superposition of, say, two states, 0 and 1 (a quantum state called a qubit). In their paper, the GHZ state involved entangling four qubits such that the entire system was in a two-dimensional quantum superposition of states 0000 and 1111. If you measured one of the photons and found it in state 0, the superposition would collapse, and the other photons would also be in state 0. The same went for state 1. In the late 1990s Zeilinger and his colleagues experimentally observed GHZ states using three qubits for the first time.

> **"Within a few hours, the program found a solution that we scientists—three experimentalists and one theorist—could not come up with for months."**
> ***—Mario Krenn***

Krenn and his colleagues were aiming for GHZ states of higher dimensions. They wanted to work with three photons, where each photon had a dimensionality of three, meaning it could be in a superposition of three states: 0, 1 and 2. This quantum state is called a qutrit. The entanglement the team was after was a three-dimensional GHZ state that was a superposition of states 000, 111 and 222. Such states are important ingredients for secure quantum communications and faster quantum computing. In late 2013 the researchers spent weeks designing experiments on blackboards and doing the calculations to see if their setups could generate the required quantum states. But each time they failed. "I thought, 'This is absolutely insane. Why can't we come up with a setup?'" Krenn says.

To speed up the process, Krenn first wrote a computer program that took an experimental setup and calculated the output. Then he upgraded the program to allow it to incorporate in its calculations the same building blocks that experimenters use to create and manipulate photons on an optical bench: lasers, nonlinear crystals, beam splitters, phase shifters, holograms, and the like. The program searched through a large space of configurations by randomly mixing and matching the building blocks, performed the calculations and spat out the result. MELVIN was born. "Within a few hours the program found a solution that we scientists—three experimentalists and one theorist—could not come up with for months," Krenn says. "That was a crazy day. I could not believe that it happened." Then he gave MELVIN more smarts. Anytime it found a

setup that did something useful, MELVIN added that setup to its toolbox. "The algorithm remembers that and tries to reuse it for more complex solutions," Krenn says.

It was this more evolved MELVIN that left Krenn scratching his head in a Viennese café. He had set it running with an experimental toolbox that contained two crystals, each capable of generating a pair of photons entangled in three dimensions. Krenn's naive expectation was that MELVIN would find configurations that combined these pairs of photons to create entangled states of at most nine dimensions. But "it actually found one solution, an extremely rare case, that has much higher entanglement than the rest of the states," Krenn says.

Eventually he figured out that MELVIN had used a technique that multiple teams had developed nearly three decades ago. In 1991 Xin Yu Zou, Li Jun Wang and Leonard Mandel, all then at the University of Rochester, designed one method. And in 1994 Zeilinger, then at the University of Innsbruck in Austria, and his colleagues came up with another. Conceptually these experiments attempted something similar,

"It was kind of clear from the beginning [that such an] experiment wouldn't exist if it hadn't been discovered by an algorithm."
—Nora Tischler

but the configuration that Zeilinger and his colleagues devised is simpler to understand. It starts with one crystal that generates a pair of photons (A and B). The paths of these photons go right through another crystal, which can also generate two photons (C and D). The paths of photon A from the first crystal and of photon C from the second overlap exactly and lead to the same detector. If that detector clicks, it is impossible to tell whether the photon originated from the first or the second crystal. The same goes for photons B and D.

A phase shifter is a device that effectively increases the path a photon travels as some fraction of its wavelength. If you were to introduce a phase shifter in one of the paths between the crystals and kept changing the amount of phase shift, you could cause constructive and destructive interference at the detectors. For example, each of the crystals could be generating, say, 1,000 pairs of photons per second. With constructive interference, the detectors would register 4,000 pairs of photons per second. And with destructive interference, they would detect none: the system as a whole would not create any photons even though individual crystals would be generating 1,000 pairs a second. "That is actually quite crazy, when you think about it," Krenn says.

MELVIN's funky solution involved such overlapping paths. What had flummoxed Krenn was that the algorithm had only two crystals in its toolbox. And instead of using those crystals at the beginning of the experimental setup, it had wedged them inside an interferometer (a device that splits the path of, say, a photon into two and then recombines them). After much effort, he realized that the setup MELVIN had found was equivalent to one involving more than two crystals, each generating pairs of photons, such that their paths to the detectors overlapped. The configuration could be used to generate high-dimensional entangled states.

Quantum physicist Nora Tischler, who was a Ph.D. student working with Zeilinger on an unrelated topic when MELVIN was being put through its paces, was paying attention to these developments. "It was kind of clear from the beginning [that such an] experiment wouldn't exist if it hadn't been discovered by an algorithm," she says.

Besides generating complex entangled states, the setup using more than two crystals with overlapping paths can be employed to perform a generalized form of Zeilinger's 1994 quantum interference experiments with two crystals. Aephraim Steinberg, an experimentalist who is a Toronto colleague of Krenn's but has not worked on these projects, is impressed by what the AI found. "This is a generalization that (to my knowledge) no human dreamed up in the intervening decades and might never have done," he says. "It's a gorgeous first example of the kind of new explorations these thinking machines can take us on."

In one such generalized configuration with four crystals, each generating a pair of photons, and overlap-

ping paths leading to four detectors, quantum interference can create situations where either all four detectors click (constructive interference) or none of them do so (destructive interference). Until recently, carrying out such an experiment had remained a distant dream. Then, in a March preprint paper, a team led by Lan-Tian Feng of the University of Science and Technology of China, in collaboration with Krenn, reported that they had fabricated the entire setup on a single photonic chip and performed the experiment. The researchers collected data for more than 16 hours: a feat made possible because of the photonic chip's incredible optical stability, something that would have been impossible to achieve in a larger-scale tabletop experiment. For starters, the setup would require a square meter's worth of optical elements precisely aligned on an optical bench, Steinberg says. Besides, "a single optical element jittering or drifting by a thousandth of the diameter of a human hair during those 16 hours could be enough to wash out the effect," he says.

During their early attempts to simplify and generalize what MELVIN had found, Krenn and his colleagues realized that the solution resembled abstract mathematical forms called graphs, which contain vertices and edges and are used to depict pairwise relations between objects. For these quantum experiments, every path a photon takes is represented by a vertex. And a crystal, for example, is represented by an edge connecting two vertices. MELVIN first produced such a graph and then performed a mathematical operation on it. The operation, called perfect matching, involves generating an equivalent graph in which each vertex is connected to only one edge. This process makes calculating the final quantum state much easier, although it is still hard for humans to understand.

That changed with MELVIN's successor THESEUS, which generates much simpler graphs by winnowing the first complex graph representing a solution that it finds down to the bare minimum number of edges and vertices (such that any further deletion destroys the setup's ability to generate the desired quantum states). Such graphs are simpler than MELVIN's perfect matching graphs, so it is even easier to make sense of any AI-generated solution. Renner is particularly impressed by THESEUS's human-interpretable outputs. "The solution is designed in such a way that the number of connections in the graph is minimized," he says. "And that's naturally a solution we can better understand than if you had a very complex graph."

Eric Cavalcanti of Griffith University in Australia is both impressed by the work and circumspect about it. "These machine-learning techniques represent an interesting development. For a human scientist looking at the data and interpreting it, some of the solutions may look like 'creative' new solutions. But at this stage, these algorithms are still far from a level where it could be said that they are having truly new ideas or coming up with new concepts," he says. "On the other hand, I do think that one day they will get there. So these are baby steps—but we have to start somewhere."

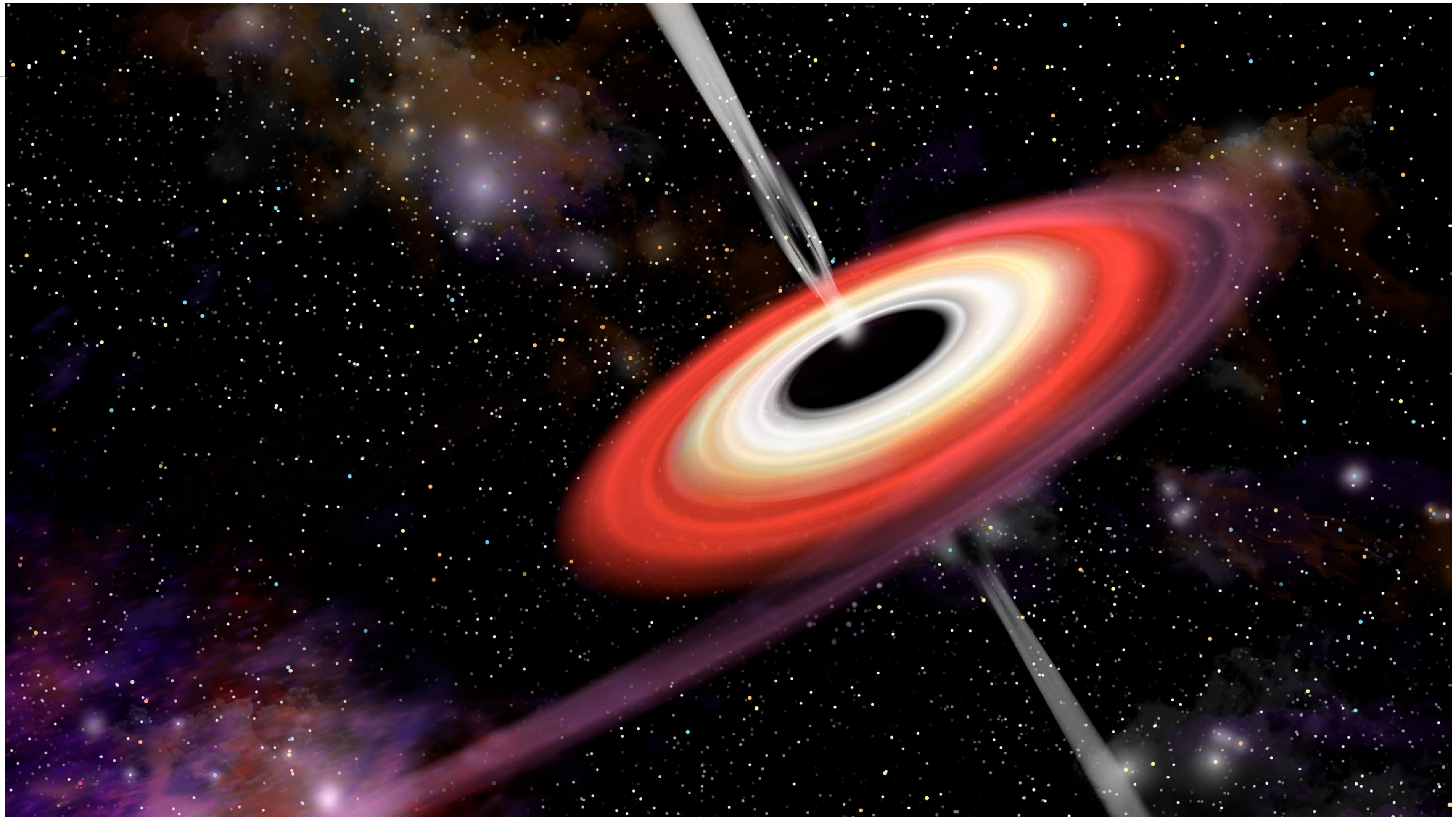
Steinberg agrees. "For now they are just amazing tools," he says. "And like all the best tools, they're already enabling us to do some things we probably wouldn't have done without them." *—Anil Ananthaswamy*

Singularities Can Exist Outside Black Holes—in Other Universes

Recent work has shown how "naked singularities" might defy the cosmic censorship conjecture

Black holes are often described as dangerous destructive entities that never give up what falls into their grasp. But what if black holes are protective—shielding us from the unpredictable effects of places where our physical understanding of the universe breaks down? This question might sound flippant, but in fact, it is at the heart of a decades-long physics puzzle known as "cosmic censorship," one that researchers may finally be close to answering.

Inside black holes, physics as we know it ends. Our current theory of gravity, Einstein's general theory of relativity, predicts its own failure at points in spacetime called "singularities." According to the equations, at these points, gravitational fields behave unpredictably, often intensifying to impossibly, infinitely high levels



Marc Ward Getty Images

where the equations themselves cannot describe what happens.

The foundational tenets of physics demand that the real, physical world continues to make sense inside black holes. They tend to interpret this breakdown of the math to mean that some as yet unknown physics, which likely involves quantum mechanics, takes over near the singularities. But until they have found a theory that unifies gravity and quantum physics, exactly what happens at those points cannot be known.

Thankfully, with the singularities tucked inside the black holes, we do not have to worry about their potentially bizarre effects on the external world. But what if these singularities could show up outside—on their own? The implications could be huge. Because we do not yet have a complete theory to describe what happens in singularities, we cannot trust the story that general relativity tells us. "Naked singularities cause general relativity to lose its predictive power," says Yen Chin Ong, a physicist at Yangzhou University in China, who has studied the nature of singularities in gravitational theories.

During the 1960s, British physicist Roger Penrose was in the midst of work on the mathematics of black holes and singularities that would later earn him the 2020 Nobel Prize in Physics. At that time, no one had turned up any compelling evidence that the equations of general relativity could describe these uncovered singularities in a physically sensible universe. They only ever materialized cloaked inside a black hole. Penrose pieced together clues that suggested a conjecture—an informed guess, not an airtight proof—that general relativity would never make that prediction. This conjecture is known as cosmic censorship: somehow the math must work out so that nature censors those "naked" singularities from existence.

Cosmic censorship is an idea that sounds to physicists like it must be right, and most assume it is. Although researchers have suggested ways to spot naked singularities—observable signs that could distinguish them from black holes—astronomers have not yet seen any evidence of them. Nevertheless, after more than 50 years, no one has proved or disproved Penrose's conjecture.

In the first few decades after Penrose's initial work, theoretical studies supported the idea that cosmic censorship would hold. Then, in 2010, physicists Luis Lehner and Frans Pretorius used a computer simulation to show that the outer surface of black holes could break into pieces and leave behind naked singularities. The fracturing comes with a curious twist, though. It happens through a process, the

so-called Gregory-Laflamme instability, that can only happen in universes with more than three dimensions of space. In other words, these sorts of singularity-revealing instabilities should be impossible in our universe's three dimensions as described by general relativity.

Despite this caveat, the result still has meaning. With this one example as a starting point, researchers can look for similar processes and ask, "Does something like that happen in our universe?" If the answer is no, they can ask, "Why not?" Pau Figueras, a physicist at Queen Mary University of London, says that this approach does not equate to a full proof but that it is still persuasive. "If this particular process is the only way to violate cosmic censorship," he says, "and astrophysical black holes do not suffer from it, then this offers a way to prove that [Penrose's] conjecture is true in astrophysical spacetimes."

Lehner and Pretorius's result inspired a new burst of interest in cosmic censorship. According to Figueras, the field has gained momentum in the past decade, thanks largely to advances in computing that have made it possible to calculate how black holes evolve and, in some cases, fall apart to reveal singularities. "It's not only that the computers needed weren't available 20 years ago," he says. "We didn't understand how to simulate general relativity and hence black holes in computers." The result, he says, is that yes, naked singularities are more common than expected—in universes with extra dimensions.

Figueras and his colleagues have demonstrated, for instance, that naked singularities can show up when black holes collide. Such collisions happen even in our universe. But the researchers found that such events in our universe do not produce the same result—a collision always ends with the singularity still wrapped inside a black hole.

A full proof or conclusive refutation of Penrose's cosmic censorship conjecture remains elusive. Whether or not the conjecture holds, though, the puzzle itself is no longer the main point for most theorists, Ong says. "It is what we can learn along the way, what insights we can gain, what tools we can develop," he adds. "The journey will be important, not just the destination."

—Brendan Z. Foster

Astronomers Thrill at Giant Comet Flying into Our Solar System

The huge object may be the biggest comet ever seen. And it is already showing signs of activity as it approaches the orbit of Saturn

Far beyond the orbits of Neptune and Pluto, a dark and mysterious expanse of space tantalizes astronomers. Here, as many as trillions of comets are thought to swarm, hurled to their present locale by Jupiter or other planets billions of years ago. They form a giant sphere known as the Oort cloud that envelops the solar system and stretches out to perhaps a couple of light-years from the sun. No one really knows just how many comets exist in the Oort cloud or its true extent because so little illuminating sunlight reaches that remote region. But occasionally a passing star or galactic tides will stir these icy leftovers from the solar system's dawn, causing comets to fall toward the distant sun and into the observability of our telescopes. These so-called long-period comets have an orbit of thousands or millions of years and are predominantly small, no more than a few kilometers across. Yet in June astronomers announced the discovery of one with truly behemoth proportions: a giant comet that may measure hundreds of kilometers from edge to edge. "It was pretty shocking," says Pedro Bernardinelli of the University of Pennsylvania, one of the researchers who found the object. Now efforts to train more telescopes in the comet's direction to unearth its secrets of the deep are well underway.

Initially dubbed 2014 UN271, the object has been officially named C/2014 UN271 (Bernardinelli-Bernstein) for its discoverers: Bernardinelli and his University of Pennsylvania colleague Gary Bernstein. It was first observed in 2014 by a project called the Dark Energy Survey (DES), but Bernardelli and Bernstein only found the comet recently, after it popped out of their analysis of the 80,000 or so images taken by DES over the past several years. The images from 2014 revealed it to be lurking at about 30 times the distance between Earth and the sun, or 30 astronomical units (AU). Now, seven years on, the object is at 20 AU and continu-

ing to approach us. Its closest point to the sun will be 10.9 AU, which it will reach in January 2031. That is not too much farther out than the orbit of Saturn—close enough that some have even envisaged sending a spacecraft to the object on a fleeting visit. Current estimates suggest the comet takes three million years to orbit the sun, traveling out to a distance of nearly 0.9 light-year—well into the Oort cloud—before swooping in again.

Both the object's size and its looming proximity have captivated astronomers. "It's very exciting," says David Jewitt of the University of California, Los Angeles. Despite receiving 400 times less sunlight than Earth's surface at its current location, the comet is bright enough to be seen by telescopes, which hints that its size must be somewhere between 100 and 370 kilometers. The uncertainty arises because of the object's unknown reflectivity and shape. But at either end of the scale, this estimate would still make it much bigger than any previously known comet. The next largest in terms of its nucleus—Hale-Bopp, which wowed stargazers in 1997—measured a relatively paltry 60 kilometers across. The Bernardinelli-Bernstein comet is "certainly the largest comet we've seen in the modern astronomical era," says Alan Fitzsimmons of Queen's University Belfast. "We've had tremendously bright comets over recorded history, but that was before the invention of the telescope [in the 17th century]."

Efforts to study the object since it was announced have been swift. Already a team of astronomers has been able to detect signs of activity, most likely melting ices forming an atmosphere, or "coma," around its solid nucleus, confirming it to be a comet. "Its brightness has increased a lot, which means that it's active," says Rosita Kokotanekova of the European Southern Observatory, who led the observations using a network of telescopes in the Southern Hemisphere. Getting continued rapid observations will be crucial in learning more about the comet. "There might still be a possibility we can see a rotational signal from the nucleus," Kokotanekova says. "When the activity gets stronger, it will be completely obscured."

Observing that activity will be enlightening, too, "because we've never observed a comet being active so far out [from the sun]," Kokotane-

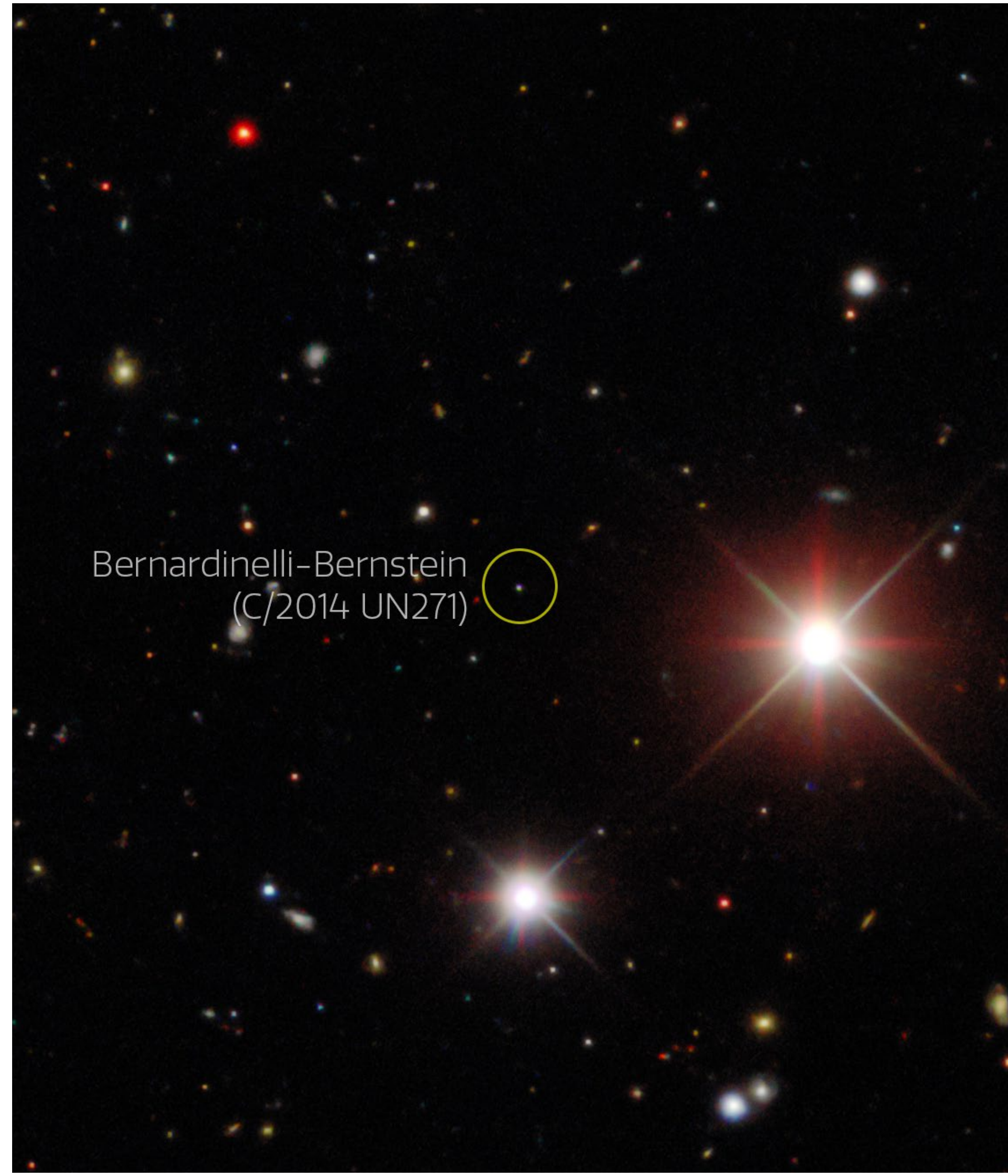


Image of C/2014 UN271 (Bernardinelli-Bernstein), the largest comet discovered in modern times. It is set to reach the vicinity of Saturn's orbit in 2031 on its inward journey from the outskirts of the solar system.

Dark Energy Survey/DOE/FNAL/DECam/CTIO/NOIRLab/NSF/AURA/P. Bernardinelli & G. Bernstein (UPenn)/DESI Legacy Imaging Surveys
Acknowledgments: T. A. Rector (University of Alaska Anchorage/NSF's NOIRLab), M. Zamani (NSF's NOIRLab) & J. Miller (NSF's NOIRLab)

kova says. This will allow researchers to probe the regions of the solar system where cometary activity begins. From the object's initial apparition in DES optics in 2014 to 2018, it did not appear to show activity, meaning it likely "switched on" at some point in the past three years, Fitzsimmons says. "It's going to give us a really nice ability to study what happens in this transition region—from being a frozen ice ball out in the Oort cloud to a fully active comet in the solar system."

At its current distance, temperatures are too low for water ice to melt, so the Bernardinelli-Bernstein comet—which may be on its first foray into the inner solar system—must have some other type of ice that is melting. "The best guess would be carbon monoxide, because we know that's present in comets, and it's also very volatile," Jewitt says.

In part because astronomers still know so little about the object and have never seen anything quite like it before, its exact nature remains unknown. Is it really a large comet or something else entirely? "Some people are speculating it could be round, almost in hydrostatic equilibrium, which makes it go in the direction of dwarf planets," Kokotanekova says. This seems unlikely, however, given that most models suggest an icy object must be in the vicinity of 800 kilometers across before its own gravity begins sculpting it into a spherical shape. To pin down the object's true size, Jewitt says the Hubble Space Telescope is the only current facility with sufficient power to peer through the coma and resolve the size of the nucleus. But as of this writing, his formal request to study the comet using the prized orbital observatory has not been approved. Other telescopes are capable of probing different features, though, such as its composition. "It's so different from everything else we've observed that it's very likely we'll discover unexpected things," Kokotanekova says.

Being able to observe the object for such a long time as it reaches its closest point to the sun, with a decade of observations ahead, will be hugely rewarding. Astronomers will be able to watch as it evolves, perhaps changing in its activity levels or even breaking apart. "The fact we can follow this thing for the next 10 years means there's a lot of opportunity to discover more detail," says

"It's going to give us a really nice ability to study what happens in this transition region—from being a frozen ice ball out in the Oort cloud to a fully active comet in the solar system."
—Alan Fitzsimmons

Colin Snodgrass of the University of Edinburgh. And for the time being, a lot of what we might observe remains tantalizingly unknown, says Michele Bannister of the University of Canterbury in New Zealand. "This is something that's been in the deep freeze for eons—hundreds of thousands of years at the very shortest," she says. "And now it's being heated by the sun. What's going to happen? How active is it going to be? We don't know yet. That's going to be really fun to find out."

The comet is also a taste of what is to come in the near future of solar system astronomy. In October 2023 a new telescope in Chile called the Vera C. Rubin Observatory will begin a 10-year survey of the entire overhead sky called the Legacy Survey of Space and Time (LSST). Thanks in part to its eight-meter mirror, Rubin will be able to discover much fainter objects than any of its predecessors, including many more expected large comets like this. "Typical telescopes find objects out to 50 or 60 AU," says LSST team member Mario Jurić of the University of Washington. "With LSST, we can easily go out to 150 AU. We're going to see things like [the Bernardinelli-Bernstein comet] maybe on a monthly basis."

For the time being, C/2014 UN271 (Bernardinelli-Bernstein) remains the largest comet ever seen approaching the inner solar system, offering a glimpse into the secrets of our sun's outermost reaches. How it behaves as it approaches Saturn's orbit will be thrilling to watch, and the name Bernardinelli-Bernstein likely will not be forgotten any time soon. "It will be studied for years and years," Kokotanekova says. "It's only going to become more interesting. We'll get to know it very well."

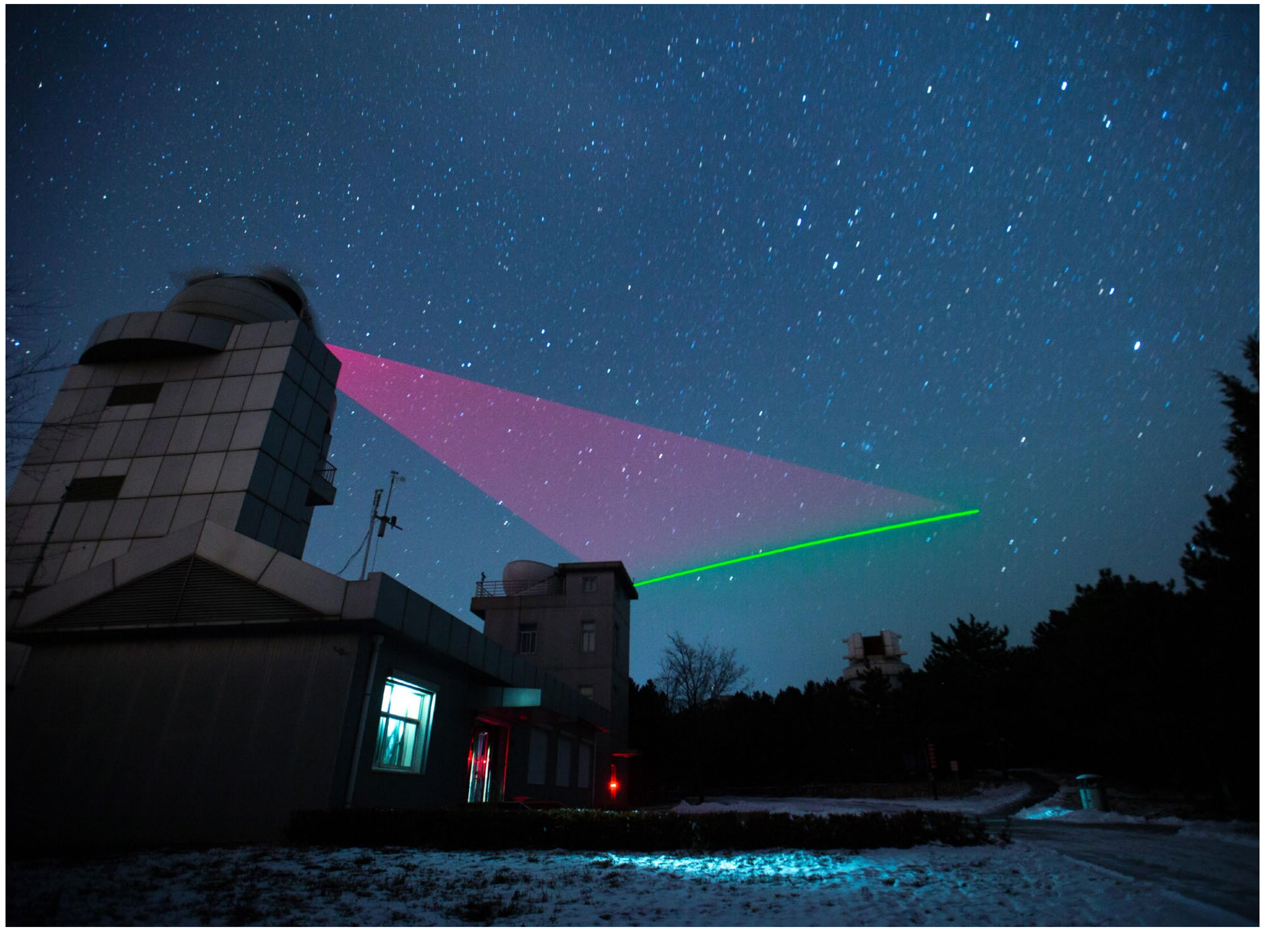
—Jonathan O'Callaghan

China Is Pulling Ahead in Global Quantum Race, New Studies Suggest

The competition between the U.S. and China over development of quantum technology has implications for both the future of science and the two countries' political relations

When a team of Chinese scientists beamed entangled photons from the nation's Micius satellite to conduct the world's first quantum-secured video call in 2017, experts declared that China had taken the lead in quantum communications. New research suggests that lead has extended to quantum computing as well.

In three preprint papers posted on arXiv.org in June, physicists at the University of Science and Technology of China (USTC) reported critical advances in both quantum communication and quantum computing. In one of the studies, researchers used nanometer-scale semiconductors called quantum dots to reliably transmit single photons—an essential resource for any quantum network—over 300 kilometers of fiber, well over 100 times farther than previous attempts. In another, scientists improved their photonic quantum computer from 76 detected photons to 113, a dramatic upgrade to its "quantum advantage," or how much faster it is than classical computers at one specific task. The third paper introduced Zuchongzhi, made of 66 superconducting qubits, and performed a problem with 56 of them—a figure similar to the 53 qubits used in Google's quantum computer Sycamore, which set a performance record in 2019.



Photograph taken on November 26, 2016, shows a link established between the quantum satellite Micius and a quantum communication ground station in the north of China's Hebei Province.

Jin Liwang *Alamy*

"It's an exciting development. I did not know that they were coming out with not one but two of these [quantum computing results] in the same week," says Scott Aaronson, a theoretical computer scientist at the University of Texas at Austin. "That's pretty insane."

All three achievements are world-leading, but Zuchongzhi in particular has scientists talking because it is the first corroboration of Google's landmark 2019 result. "I'm very pleased that someone has reproduced the experiment and shown that it works properly," says John Martinis, a former Google researcher who led the effort to build Sycamore. "That's really good for the field, that superconducting qubits are a stable platform where you can really build these machines."

Quantum computers and quantum communication are nascent technologies. None of this research is likely to be of practical use for many years to come. But the geopolitical stakes of quantum technology are high: full-fledged quantum networks could provide unhackable channels of communication, and a powerful quantum computer could theoretically break much of the encryption currently used to secure e-mails and Internet transactions.

Tensions between the U.S and China are currently at their highest point in decades, with the countries clashing over trade, human rights issues, concerns about espionage, COVID and Taiwan. After China's demonstration of the Micius satellite in 2017, American politicians responded by pushing hundreds of millions of dollars into quantum information science via the National Quantum Initiative. It was an eerie bit of déjà vu. About 60 years earlier, the U.S. was similarly spurred to fund another pie-in-the-sky initiative—space exploration—because of fearmongering over a little Soviet satellite named Sputnik.

But this struggle for quantum advantage need not be a perfect mirror of the space race. Zuoyue Wang, a science historian at California State Polytechnic University, Pomona, notes that China and the U.S. are intimately intertwined in many areas—science among them—that could prevent a hostile new competition in the quantum realm. Today hundreds of thousands of students travel from China to study in the U.S., and scientists in both countries collaborate closely on research ranging from agriculture to zoology. In spite of rising geopolitical tensions between the two countries, "they're each other's biggest international collaboration partners," Wang says.

QUBIT BY QUBIT

Forty years ago physicist Richard Feynman made a straightforward proposition: Classical computers trying to simulate a fundamentally quantum reality might be outdone by a computer that, like reality, is itself quantum. In 2019 a team at Google led by Martinis realized this so-called quantum advantage by demonstrating that the company's Sycamore system really could perform a specific, limited task exponentially faster than even powerful classical supercomputers (though a competing team at IBM disputed that Google's achievement represented a true quantum advantage). A year later USTC researchers performed a similar experiment with a quantum computer made from photons.

Why can rudimentary quantum computers beat classical supercomputers at specific tasks? The common refrain goes something like this: Instead of classical bits that are 0 or 1, a quantum computer uses qubits, whose state is somewhere in between 0 and 1 prior to measurement—a so-called quantum superposition. To work together within a computer, qubits must also be entangled, or quantum correlated with one another.

It might be more intuitive to consider the task Zuchongzhi and Sycamore have performed. "It's almost embarrassingly simple," Aaronson says. "All you do is a random sequence of quantum operations." This chaotic set of instructions entangles all the qubits into one big, messy state. Describing that state is easier for qubits than bits. Describing two entangled qubits requires four classical bits. (There are four possible outcomes: 00, 01, 10, or 11.) The state complexity scales exponentially, so what takes 50 qubits requires 2^{50}, or about one quadrillion, bits to describe. Photonic quantum computers create a similarly entangled messy state but with photons instead acting as qubits.

This is why even a small 50-qubit quantum computer can beat a massive classical supercomputer. "If you look at the West—the U.S., Europe—there haven't been a lot of people talking about repeating [Google's 2019] experiment," Martinis says. "I admire, in China, that they want to do this seriously."

With 56 qubits and 113 detected photons, the USTC systems detailed in two of the new preprints are now technically the most powerful quantum computers in the world—with two big caveats. First, neither quantum computer can do anything useful. (Photonic quantum computing is not a universal computer platform, so even scaled up, it would not be a conventional programmable computer.) Second, it is not clear exactly how much of a quantum advantage they actually have over classical computers. Over the past few months, several studies have claimed the ability to approximate that messy entangled state, especially for photonic quantum computers.

Despite the difficulties of working with photonic quantum computers, USTC researchers have good incentive to master the platform because photons are the medium of China's emerging quantum network. Already thousands of kilometers of fiber-optic cables have created an initial quantum link between Beijing and Shanghai. The link is not a fully realized quantum connection: it is divided up by nodes

because photons can only go so far without succumbing to noise in the fiber. A bona fide quantum network could have a variety of applications, but the two main ones are precision synchronization and unhackable communications.

To fulfill that promise, quantum networks will require—among other things—entangled single photons that can be used for quantum key distribution or other operations that require entanglement. Quantum dots are thought to be ideal sources for single photons. Until now, quantum dots had never sent single photons through more than about a kilometer of fiber. (Typically the longer the fiber, the greater the noise.) But the USTC team managed to increase the transmission distance while also decreasing the noisiness of the single photon. Its success came from taking strenuous measures, such as stabilizing the temperature of the 300-kilometer fiber to within a tenth of a degree Celsius.

RACING IN THE QUANTUM REALM

Is China ahead of the U.S. in quantum information technology? The answer depends on how you measure it. While estimates vary, both countries appear to fund the research to the tune of more than $100 million per year. China has more total patents across the full spectrum of quantum technology, but U.S. companies have a dramatic lead in quantum computing patents. And of course, China has a more sophisticated quantum network and now claims the top two quantum computers.

"It's such a new problem for the U.S. to be facing," says Mitch Ambrose, a science policy analyst at the American Institute of Physics. "It was ahead for so long, and in so many areas, that it hasn't really had to do much thinking about what it means to be behind."

Broadly speaking, quantum research in China is almost entirely state driven—concentrated into a few universities and companies. Research in the U.S., in comparison, is much more disparate—spread across dozens of funding agencies, universities and private companies.

"The Chinese government is thinking about science technology very seriously, probably more than the U.S. administration" Wang says. "No one else will pick up the tab."

Currently the U.S. government is determining how to fund the future of quantum information science in proposed bills such as the Innovation and Competition Act of 2021, which would provide $1.5 billion for communications research, including quantum technology. In response to security concerns about China, the bill also prioritizes semiconductor manufacturing and includes a provision that would restrict cooperation with China on nuclear energy and weaponry. This is not the first restriction on scientific collaboration between the two countries. Since 2011 NASA has been under the thumb of the Wolf Amendment, which bans any cooperation with China's space agency without a waiver. Conversely, China and the U.S. have also spent more than four decades cooperating officially on scientific matters, because of the U.S.-China Agreement on Cooperation in Science and Technology of 1979.

As tensions between the two nations continue to rise, quantum research occupies an awkward spot: although it remains basic research with limited current applications, its future strategic potential is clear and immense. "What are the rules of the road for scientific exchanges going forward in any field, let alone quantum?" Ambrose asks. Hawkish funding of quantum technology could further inflame relations, but it could also stimulate more cooperation and transparency between competing countries seeking to prove their quantum prowess.

During the cold war, the U.S. and the Soviet Union sought to demonstrate parity with, if not supremacy over, each other in nuclear weaponry, spaceflight and other strategically important technical pursuits. Olga Krasnyak, an expert in science diplomacy at the National Research University Higher School of Economics in Moscow, argues the resulting U.S.-Soviet scientific exchanges helped end the cold war. "Science diplomacy has this advantage—it uses science, which is universal," Krasnyak says.

Just as important, it uses scientists—who historically have leveraged their common humanity and shared a quest for knowledge to overcome the strain of any ideological differences. Quantum computing and communications may indeed have the power to reshape the world. But, Krasnyak says, "I believe in the power of human communication, too." *—Daniel Garisto*

This Report Could Make or Break the Next 30 Years of U.S. Astronomy

A battle for the future of American stargazing is about to begin—and the stakes are sky high

By Lee Billings

Andreas Koerberl *Getty Images*

Lee Billings is a senior editor for space and physics at *Scientific American*.

ASK ASTRONOMERS WHAT QUESTION they most want to answer, and you will get scattered responses: How did the first stars, galaxies and black holes form? What is the nature of dark matter and dark energy? Are we alone?

Each question demands its own large telescope: no ultimate, one-size-fits-all instrument will ever exist, for none can be made to gather each and every kind of cosmic light. Black holes sometimes shine in x-rays, for instance, whereas Earth-like exoplanets are best studied in optical and infrared light. Yet such projects so strain the fraction of public and private funds allocated to astronomy that only a few—perhaps just one—can be prioritized at a time, leading to pileups of also-ran proposals and anxious researchers awaiting a rare chance to open new windows on the universe.

In the U.S., astronomers have managed these competing ambitions by devising a process that has become the envy of the scientific world: the Astronomy and Astrophysics Decadal Survey, a once-in-10-years exercise that recommends and ranks the community's priorities for the next decade—embodied, eventually, by major new federally sponsored observatories on the ground and in space. Projects such as NASA's Hubble Space Telescope owe their existence, in part, to coveted endorsements from Decadals of yore, and the practice has spread to several other disciplines that now undertake Decadal Surveys of their own.

Organized by the National Academies of Sciences, Engineering, and Medicine, six Decadal Surveys have set the course of U.S. astronomy since they began in the 1960s. The results of the seventh, dubbed Astro2020, will soon be announced after two years of exhaustive deliberations led by a 20-member steering committee. And just like its predecessors, Astro2020 will reveal where major new investments and discoveries are most likely to be made—and where neglect, disinterest or even fear may block progress for generations to come.

Few people know the power of these surveys better than Joel Parriott. More than 20 years ago, he got his start in federal politics as a staffer at the National Academies, where his initial assignment was to assist the scientists crafting the first astronomy Decadal of the new millennium. Then he served a 10-year stint in the White House Office of Management and Budget (OMB), where he weighed and implemented Decadal recommendations for federal science agencies. Today he is director of public policy at the American Astronomical Society, the leading advocacy group for U.S. stargazers. At the OMB, where the nation's policy objectives often brutally intersect with its fiscal realities, the Decadal Survey offered Parriott and his colleagues a foolproof way of dismissing overly solicitous astronomers. "If a project wasn't highly ranked, we knew it didn't have the community's endorsement," he says. "That's really helpful for folks on Capitol Hill and in the White House who need to make hard choices."

For more than a few astronomers, a drab name like "the Decadal" does not properly capture a process that holds such sway over their destiny. Instead they sometimes just call it "the voice of God." In coming weeks, when Astro2020's final report is released, that voice—that supposedly communal voice—will once again speak. Yet outside of a chosen few, sworn to secrecy, no one in the community knows in advance what it will say. Everyone, though, agrees Astro2020's conclusions arrive at a time of peril.

"We are right now on a knife-edge," says John O'Meara, chief scientist of the W. M. Keck Observatory on Mauna Kea in Hawaii. "I do believe this Decadal is existential for astronomy in the United States. When you consider the facilities and the science topics that are under discussion, it will influence whether or not we become a second-place player in global astronomy.… When the [federal] agencies and Congress receive the Decadal report, they will hold in their hands the decision of whether or not we wish to have leadership in this field of science."

U.S. TELESCOPES IN TWILIGHT

From the outside looking in, one would not realize the enterprise of U.S. astronomy is teetering on the edge of

Astro2020 steering committee, panel chairs and study staff. The steering committee's co-chairs, astronomers Robert Kennicutt and Fiona Harrison, appear 14th and 16th from left, respectively.

crisis. Several new ground-based telescopes have recently come online, each bringing a bumper crop of celestial discoveries—and even more ambitious projects are waiting in the wings. Consider the Vera C. Rubin Observatory, a high-ranked priority of the past two Decadals (which are naturally called Astro2000 and Astro2010). Sited on a mountain in Chile, the Rubin Observatory should begin operations in late 2023 to generate a high-definition, decade-spanning time-lapse movie of the entire overhead sky.

But among large upcoming U.S. projects, Rubin is a rare, healthy exception. The other highest-profile ground-based recommendation from Astro2000 and Astro2010—building an optical extremely large telescope (ELT) with a mirror circa 30 meters in size—remains in limbo. One selling point for ELTs, among many, is that they offer the best hopes of ever studying Earth-like exoplanets from the ground. Astro2020 will probably decide if the U.S. ELT efforts sink or swim—or if other projects, such as a "next generation" upgrade to the nation's Very Large Array of radio telescopes or expansions of gravitational-wave observatories, take priority.

In the quest for an ELT, the U.S. has managed to produce two competing projects, the Thirty Meter Telescope (TMT) and the Giant Magellan Telescope (GMT). Both are short on funding, and neither appears likely to begin operations before the decade is out, each having served to stifle the other. And the TMT's early stages of construction on the Hawaiian volcano Mauna Kea—a site unrivaled for pristine views of the Northern Hemisphere

Artists' impressions of the Thirty Meter Telescope (*left*) and the Giant Magellan Telescope (*right*), two U.S. projects to build enormous ground-based observatories.

TMT International Observatory (*left*); GMTO Corporation and M3 Engineering (*right*)

sky—sparked protests from activists who see telescopes there as an occupying affront to the mountain, which Native Hawaiians hold sacred. Construction on the TMT ceased after protesters repeatedly blocked the road to the mountaintop; the conflict remains at an impasse. "If [Astro2020] says, 'Forget the ELTs; let's prioritize something else instead,' then it's quite possible that both the TMT and the GMT will die," says a senior ground-based astronomer familiar with the situation.

Europe, in contrast, took the lead over the U.S. in ground-based optical astronomy years ago and is well into construction of an ELT of its own in Chile. The European Extremely Large Telescope boasts a 40-meter mirror—and it is projected to come online in 2027.

China is surging ahead as well. For evidence, look no further than the U.S.'s iconic, National Science Foundation–funded Arecibo radio telescope in Puerto Rico: Once the world's largest, the radio telescope catastrophically collapsed last year in part because of budgetary neglect—but not before China's Five-Hundred-Meter Aperture Spherical Radio Telescope (FAST) had superseded it in size. And together—without the U.S.—Europe, China and many other international partners are building the Square Kilometer Array (SKA), a breathtakingly powerful collection of thousands of radio telescopes that is set to become fully operational at sites in Australia and South Africa as early as 2030.

THE HUNGRY GIANT AND FRANKENSTEIN'S MONSTER

Activists blockade the road to the summit of Mauna Kea in Hawaii, seeking to halt construction of the Thirty Meter Telescope on the sacred volcano, in this photograph from July 2019.

Ronit Fahl, *ZUMA Wire and Alamy Live News*

The outlook is similarly mixed for the nation's space-based astronomy. For now, the U.S. remains at the forefront of off-world observing, but of the four "Great Observatories" NASA launched between 1990 and 2003, only Hubble and the Chandra X-ray Observatory are still operational, and both are nearing their end, with no replacement on the horizon. "Hubble is probably not going to last another decade, and maybe we'll get five more years out of Chandra. But then that's it—they're gone," says Jason Tumlinson, an astronomer heading the community missions office at the Space Telescope Science Institute. "We'll probably have a long gap with no real optical, ultraviolet or x-ray capability in space. And now is the time to decide how and when we might get it back."

Astro2000's top-ranked space project, NASA's flagship-class James Webb Space Telescope, is a technological marvel: a cryogenically cooled infrared observatory with a segmented, 6.5-meter starlight-gathering mirror that folds, origamilike, to fit in a rocket. Early on Webb was projected to cost about $1.5 billion and to launch perhaps in 2011 to study the emergence of stars and galaxies in the early universe. Today those projections seem hopelessly naive. After a staggering number of cost overruns and delays that hobbled planning for other projects, the current best-case scenario is that the telescope will reach space no sooner than this December, operating for just a decade with a total project cost of about $10 billion. Less optimal scenarios, of which there are many, are almost too grim to contemplate. "We can't do science at this scale without taking risks—and I'm confident in our chances of success—but if Webb fails, it will be an unmitigated disaster," says Matt Mountain, the project's telescope scientist and president of the Association of Universities for Research in Astronomy. "It has to work. Because if it doesn't, we aren't going to do another ambitious flagship for, I would guess, two decades."

If Webb was a hungry giant unleashed by Astro2000 and its antecedents biting off more than could be chewed, then the top flagship recommendation of Astro2010, NASA's Nancy Grace Roman Space Telescope, was a different beast entirely—a cut-rate Frankenstein's monster the Decadal committee pieced together from the dismembered remains of multiple competing mission concepts. The committee had hoped to avoid another Webb-style debacle with Roman (initially named the Wide-Field Infrared Survey Telescope, or WFIRST)—and it did. But instead Roman's very existence threatened to tear the community apart from within. "Do you know what WFIRST really stood for, for most of us?" says one leading astronomer. "It stood for 'What the fuck is this ridiculous space telescope?'"

Originally envisioned to study dark energy with a bare-bones instrument package and a mirror scarcely half the size of Hubble's, Roman was projected to launch as early as 2020 on a relatively slim budget of less than $2 billion. To many expert eyes, such a project barely qualified for its supposed "flagship" status. NASA, with bipartisan congressional blessings, ultimately added more instruments and upgraded Roman's mirror to the same size as Hubble's, enhancing its science objectives and assuaging

many criticisms—but also nearly doubling its estimated price tag and delaying its launch to no earlier than 2025. Meanwhile Europe and China have each proceeded with dark energy–focused space telescopes of their own, potentially scooping some of the promised scientific discoveries used to justify Roman's existence in the first place.

Although both Webb and Roman may each eventually succeed beyond astronomers' wildest imaginings, some fear the projects' greatest initial impact on the field will be to sharply curtail Astro2020's ability to plan for a prosperous future. "This is, I think, the first Decadal where both of the top space-based recommendations from the previous two Decadals—Webb and Roman—were still on the ground," Tumlinson says. "And if the Astro2020 committee were to say, 'We've got two flagships stacked up; the queue is too long; let's just pause for a while and do some smaller missions and catch up later,' that would be a mistake. The idea that you can just take a decade off from ambitious things to come back and do them later is not valid when you consider how our government actually works."

Most astronomers, Tumlinson says, seem to misunderstand what the Decadal's "governing dynamic" actually is. "A Decadal report is the beginning of a multiparty, multiyear negotiation between the scientific community, NASA, the aerospace contractors, Congress and the White House," he explains—which is why aiming high at the outset is in astronomers' best interest. "I would hope, with Astro2020, we temper our natural desire to mitigate risk and cut costs," Tumlinson says, "because all the other forces in this system will be doing that for us anyway."

Whether because of the COVID-19 pandemic, soaring deficit spending or the increasingly dire global climate emergency, some might question the wisdom of U.S. astronomers reaching for the stars just as the sky seems set to fall. Then again, the reply comes, where is the wisdom in limiting the science of the 2040s or 2050s based on the troubles of the 2020s? "At the end of the day, appropriators are still going to spend money," says a former congressional staffer who dealt with high-level appropriations for federal science agencies. "They're going to get an allocation, and their job will be to use it wisely. If it doesn't go to astronomy, maybe it will go to a new flagship mission for NASA's planetary science division instead—or maybe it will go to a new FBI building. But that money will be spent, regardless of what astronomers do."

Technicians examine the 6.5-meter segmented primary mirror and deployable sun shield of the James Webb Space Telescope, NASA's $10-billion "flagship" observatory, which is scheduled to launch in December.

Chris Gunn *NASA*

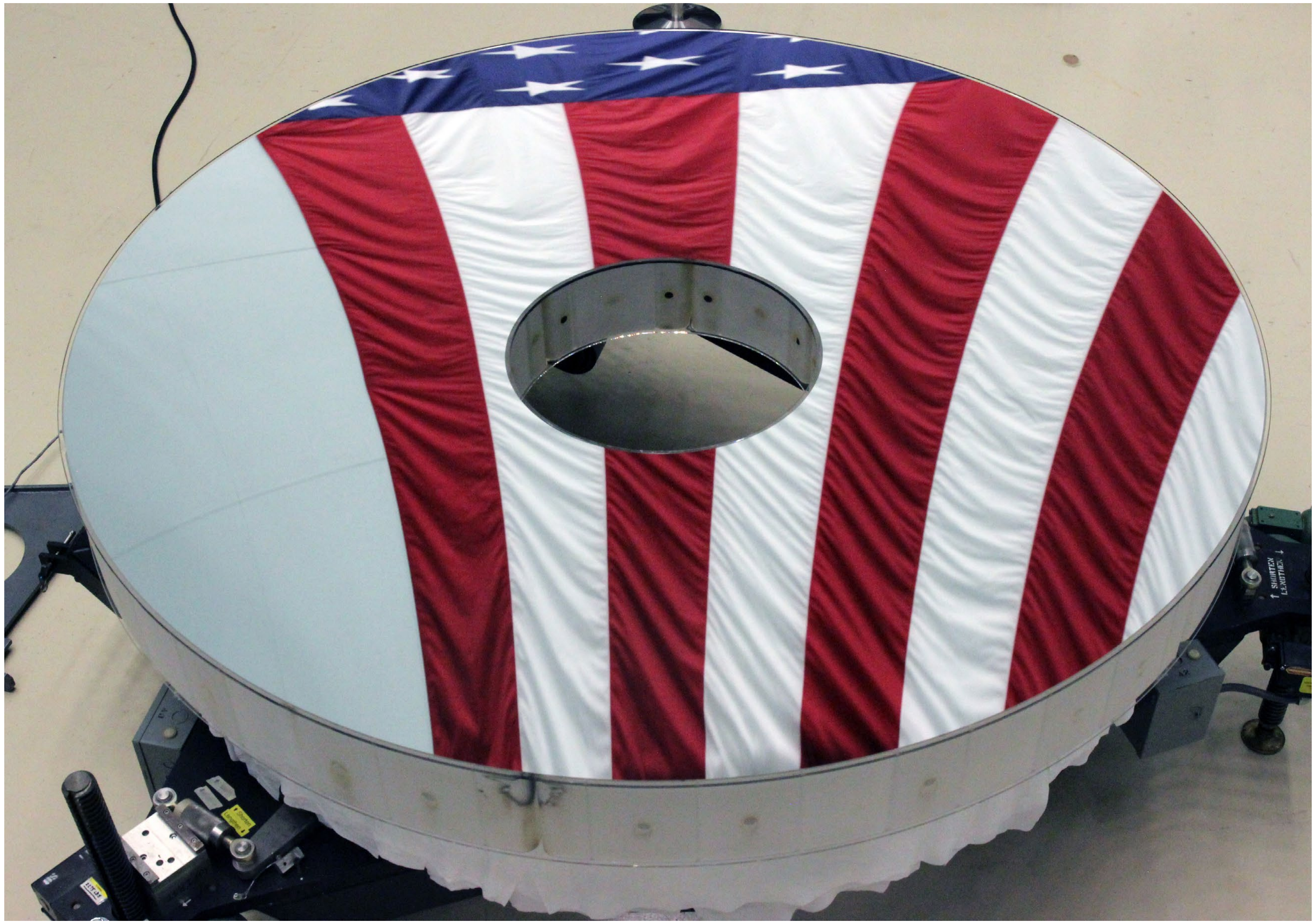
THE MAIN MENU

Responding to the woes from Webb and Roman, years ago NASA began revamping its approach to future flagships, demanding greater certainty about technological challenges and costs. In 2016 the agency assembled four Science and Technology Definition Teams (STDTs), each examining a separate mission concept for Astro2020's

consideration. Two of the four concepts—the Large Ultraviolet Optical Infrared Surveyor (LUVOIR) and the Habitable Exoplanet Observatory (HabEx)—would focus on the quest to learn more about planets orbiting other stars, with an emphasis on studying potentially habitable worlds. A third, the ultracold and far-infrared Origins Space Telescope, would also perform some exoplanet studies as part of a broader investigation of the formation of galaxies, stars and planetary systems. The fourth concept, the Lynx X-ray Observatory, would be the most powerful x-ray astronomy facility ever built, offering intimate views of black holes, active galaxies and violent supernovae across cosmic time. Each project has profound potential—but also one or more Achilles' heels to make astronomers antsy.

LUVOIR's strength—and weakness—has always been the huge size of its segmented mirror. If deployed and maintained with picometer-degree stability (which is very hard), this mirror would allow astronomers to discover and study hundreds of exoplanets while also performing revolutionary observations across a wide swath of general astrophysics. Assuming any true-blue Earth-like worlds exist around the sun's neighboring stars, LUVOIR should offer the best odds of finding them. But whether considering either a 15-meter "deluxe model" or an eight-meter "budget size" one, putting such a demanding deployable mirror into space translates to an astronomical cost. "When I started working on this, I closed my eyes and said, 'It's gonna be $1 billion a meter. But if LUVOIR realizes its vision, that would be a bargain," says O'Meara, one of the leaders of the this mission concept's STDT. Estimates from two separate groups at NASA's Goddard Space Flight Center have arrived at slightly higher figures, placing a deluxe LUVOIR somewhere in the realm of $15 billion or $20 billion and finding the budget version between about $12 billion or $15 billion.

Thanks to its smaller four-meter mirror, HabEx would



View of the 2.4-meter primary mirror of NASA's Nancy Grace Roman Space Telescope, the next flagship observatory to fly after Webb.

L3Harris Technologies, Inc.

be cheaper than either version of LUVOIR, with an estimated cost approaching $10 billion. But it would yield far fewer exoplanets—delivering details on perhaps 10 potential exo-Earths rather than dozens. It represents an all-in bet on a novel technology: a secondary sunflower-shaped spacecraft called a "starshade" that would unfurl to more than 50 meters across and fly more than 75,000 kilometers in front of the four-meter mirror to blot out a target star's light, revealing comparatively dimmer accompanying worlds. "The starshade concept, although potentially very powerful, scares a lot of people for whom it is a relatively new idea," says Scott Gaudi, an astronomer at the Ohio State University, who co-chaired the HabEx STDT. Yet he maintains that scientists have a realistic plan for managing risks and developing the starshade on budget.

Origins is, in most respects, the "safe" choice: it features a large but nonsegmented mirror of nearly six meters and is based mostly on preexisting technologies,

netting a cost estimate of around $7 billion. Chilled to less than five kelvins above absolute zero, the telescope would offer a 1,000-fold increase in far-infrared sensitivity over previous missions, allowing astronomers to map the inner workings of galaxies across the observable universe while also studying a handful of small exoplanets as well as water in protoplanetary disks around nearby stars. But Origins's tried-and-true approach makes it relatively bland: It would not answer the burning questions about Earth-like worlds that LUVOIR or HabEx might. Its infrared optics would not deliver the crisp, colorful images of Hubble. And a top ranking from Astro2020 would make it, after Webb and Roman, the third infrared flagship in a row recommended to NASA. Some might call Origins a space telescope only an astronomer could love. "We have a real PR problem in the infrared," says Cara Battersby, an astronomer at the University of Connecticut, who served on the Origins STDT. "But if you look at the specs of each [STDT] concept and the science questions they have in common, such as planets and the coevolution of black holes with galaxies, I challenge you to not conclude that Origins is the most well rounded and safest of them all."

Lynx is the oddball of the four, with a projected price tag slightly shy of that of Origins but a radically different design and goal. Its "mirror" would be a first-of-its-kind three-meter-wide assembly of nearly 460 nested shells of polished silicon, all densely packed and angled to reflect and focus high-energy x-rays. That design would provide far better performance than Chandra or other earlier x-ray telescopes, allowing Lynx to unveil new details of the universe's oldest and biggest black holes. Some astronomers fret about potential budget-busting difficulties in making Lynx's exotic mirror, but most instead worry about duplicating the efforts of a similar, already approved project: the European Space Agency's Advanced Telescope for High-Energy Astrophysics (Athena), which is set to launch in 2031. "For many people, the existence of Athena is an insurmountable argument against Lynx," says Grant Tremblay, an astronomer and a contributor to the Lynx STDT at the Center for Astrophysics at Harvard University and the Smithsonian Institution. "But I sincerely believe there is a very compelling argument for why these two missions are scientifically complementary to each other."

"I'm utterly convinced a 'New Great Observatories' program with Lynx, Origins, and LUVOIR or HabEx—a 'LuvEx,' so to speak—could be done with a single phone call to the right person."
—Grant Tremblay

Collectively, these four STDT concepts make up the main menu of flagship options that the Astro2020 steering committee is most likely to choose from—presuming, that is, the committee picks one at all. All four projects are subject to Astro2020's Technical Risk and Cost Evaluation (TRACE) process, a brand-new, behind-closed-doors checkup by the Aerospace Corporation on each STDT concept's estimates. If the TRACE deems all four concepts far more expensive than the STDTs' in-house estimates, the steering committee could opt to choose none.

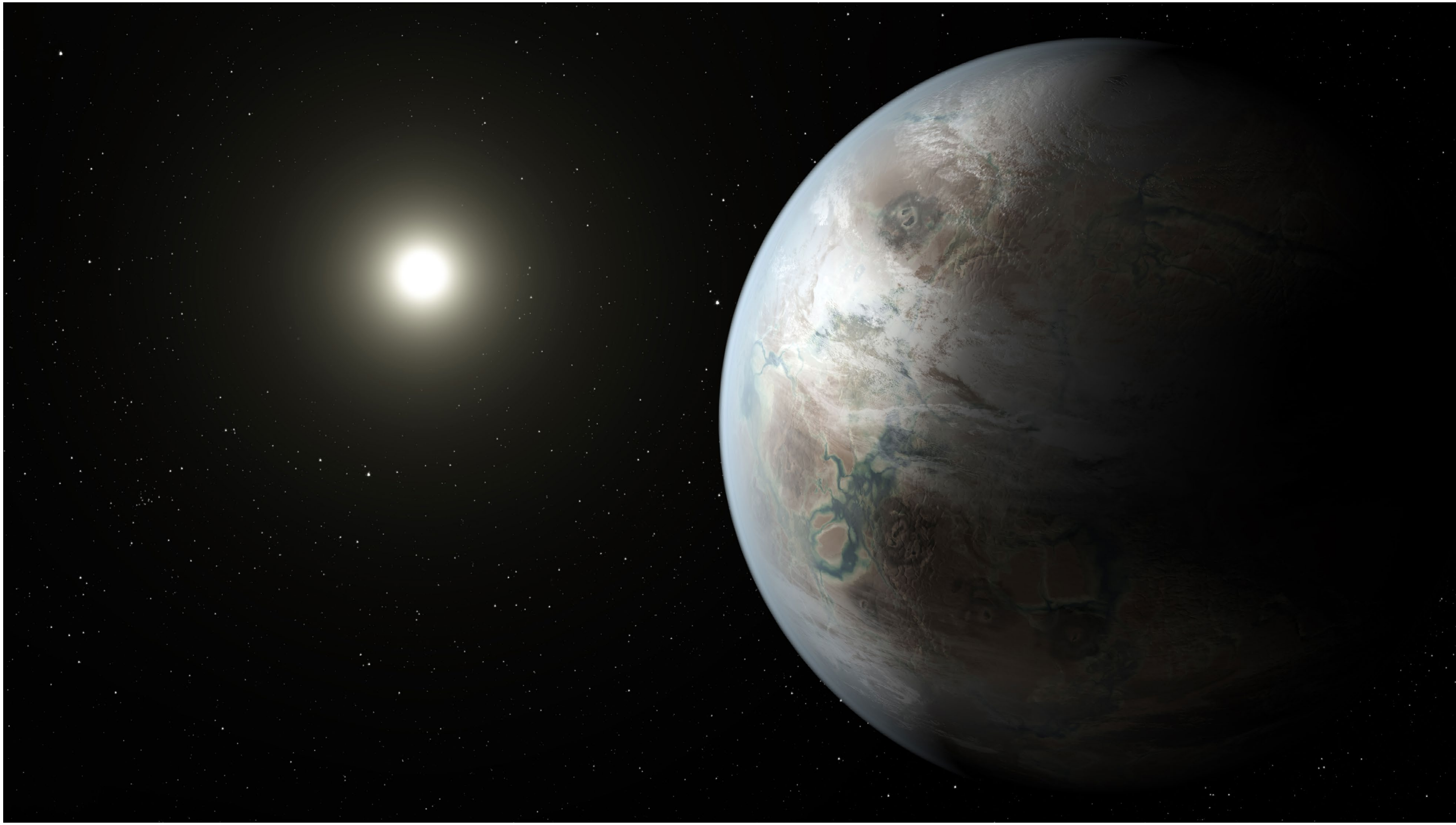
THE NEW GREAT OBSERVATORIES

Astronomers have named the four likeliest outcomes of the Astro2020 deliberations: "Scenario one, we call 'the shit sandwich,' which is if they recommend no flagships," says one senior scientist. "Most of us think that would be disastrous. The 'shit sandwich with a side of pickle' is when they choose no flagships but recommend technology development for whatever could come next—which is close to what happened with Astro2010. The 'nice lunch' is what we get if they pick a true flagship. And the 'perfect meal' is their picking a flagship and setting priorities for technology development to enable a few more."

For now, most members of the STDTs are lining up for a "perfect meal." Remarkably, after years spent extolling the virtues of their chosen missions, they have almost universally concluded that the ideal future for U.S. astronomy in space is one in which none of their pet projects triumph over all but rather where multiple flagships are somehow built and launched in rapid succession. Such an approach would effectively create a "New Great Observatories" program for the 21st century, much like the one that produced Hubble and its epochal kin. "I've promised—and many of my colleagues have, too—that if the Decadal chooses any flagship, then that is what I'll be cheering for," O'Meara says. "Something like the New Great Observatories can only happen if we stop shooting into each other's backyards."

Or rather the New Great Observatories can only happen if astronomers become more savvy at what Gaudi has termed "astropolitics." "I'm utterly convinced a 'New Great Observatories' program with Lynx, Origins, and LUVOIR or HabEx—a 'LuvEx,' so to speak—could be done with a single phone call to the right person," Tremblay says. "Because on Capitol Hill, it's not about total cost—it's about annual appropriation. A couple hundred million dollars a year added to NASA's astrophysics line would suffice."

Such hopeful speculations are not necessarily just wishful thinking. "We're talking a 1 or 2 percent increase



An artist's impression of an Earth-like exoplanet orbiting a star similar to our own sun. When and whether such worlds are discovered and studied in detail for signs of habitability and life may depend a great deal on the outcome of Astro2020.

NASA Ames, JPL-Caltech and T. Pyle

in real dollars to NASA's budget to enable another Great Observatories program," says one Beltway insider. "These are the perturbations concerted advocacy can create. Only about 30 senators are really involved in appropriations, and the annual discretionary budget of the federal government is running at about $2 trillion. So divide $2 trillion by 30 and then factor in the staffers working for each of those senators. You'll find, perhaps to your horror, that anything much below about half a billion dollars a year is essentially left to staffers and lost in the margins." Tremblay puts it more bluntly. "NASA does not really work for the Executive Office of the President," he says. "It works for the 25-year-olds a few years out of college who serve on appropriations committees. A flagship mission—or a whole new series of Great Observatories—could be green-lit over lunch by some low-level staffer while they're eating a burrito."

A SINGLE QUESTION

To secure a multiflagship future, astronomers will likely need an overarching goal that resonates not only with professional scientists but also with policy makers and the general public they serve (burrito-munching congressional staffers included). And for that, arguably no topic has broader appeal than humankind's long, unrequited search for alien life.

"If the Decadal wants to get the most public buy-in, they should distill the next 30 years of U.S. astronomy down to a single question: How does the universe enable biology?" O'Meara says. "Think about what's needed to get answers for that. It's not just going out and taking pictures of small, temperate exoplanets. You need to track the creation of atoms and molecules from the big bang all the way to planetary biosignatures, and you need to understand how galaxies and stars arise so that the universe could make planets in the first place. You also need to understand where life can and cannot exist, which means deeper exploration of the solar system and probably even sending astronauts to Mars. Addressing that single, fundamental question could speak to all of NASA while bringing in the NSF and international partners as well."

"This is another reason to consider Astro2020 'special,'" Tumlinson says. "For the first time, we can say with a straight face that we're conceptually designing missions with reasonable expectations of finding life on planets outside the solar system. And to not do that when you have the opportunity to—well, that seems a little crazy to me."

Yet many astronomers are also uneasy about promising more than they might be able to deliver. "This mentality, that we all must be behind one big thing and that this one thing has to be so big to justify us all being behind it, is exactly how we've gotten into trouble before," says Sara Seager, an astrophysicist at the Massachusetts Institute of Technology, who, alongside Gaudi, co-chaired the HabEx STDT. "Of course looking for other Earths has public support! But if you put a dollar figure on it—if you tell the public it may cost a half-billion or a billion per planet, what do you think they'll say then? It just so happens that we live on a really hard planet to find—Earths are small and faint, and they're right next to big, bright stars. That makes seeing them—or searching for signs of life on them—nearly impossible."

At least, that is the case if astronomers try to achieve those goals within existing budgets and a Decadal's 10-year time frame. "For us to decide on the future of astronomy based on some arbitrary length of time that just happens to be the number of fingers we have on our hands may not be the best way to go about things," Gaudi says. "Maybe we should decide on a different, longer timespan that actually corresponds to the missions we're considering—missions that are getting more ambitious, complicated and technologically challenging over time. These really aren't 'Decadal' surveys anymore, and they haven't been for a while. They're multidecadal surveys, and we just need to start being honest about that."

After experiencing the process and its imperfections from within the National Academies, the White House and now the largest advocacy group for U.S. astronomers, Parriott offers a simple recommendation of his own. "We need to support the Decadal, because it's probably the best we can hope for in planning and executing a program of benefit to all of us," he says. "You know that old saying about democracy? Well, maybe it applies to the Decadal, too: it's the worst way to do things—except for all the other ways." SA

Star Trek's Warp Drive Leads to New Physics

Researchers are taking a closer look at this science-fiction staple–and bringing the idea a little closer to reality

By Robert Gast

Getty Images

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FOR ERIK LENTZ, IT ALL STARTED WITH *STAR TREK*. EVERY FEW EPISODES OF *STAR Trek: The Next Generation*, Captain Jean-Luc Picard would raise his hand and order, "Warp one, engage!" Then stars became dashes, and light-years flashed by at impossible speed. And Lentz, still in elementary school, wondered whether warp drive might also work in real life.

"At some point, I realized that the technology didn't exist," Lentz says. He studied physics at the University of Washington, wrote his Ph.D. dissertation on dark matter and generally became far too busy to be concerned with science fiction. But then, at the start of the coronavirus pandemic, Lentz found himself alone in Göttingen, Germany, where he was doing postdoctoral work. He suddenly had plenty of free time on his hands—and childhood fancies in his head.

Lentz read everything he could find on warp drives in the scientific literature, which was not very much. Then he began to think about it for himself. After a few weeks, something occurred to him that everyone else seemed to have overlooked. Lentz put his idea on paper and discussed it with more experienced colleagues. A year later it was published in a physics journal.

It quickly became clear that Lentz was not the only person dreaming about warp drives. Media outlets all over the world picked up the story, and a dozen journalists asked for interviews. A discussion on the online forum Reddit attracted 2,700 comments and 33,000 likes. One Internet user wrote, "Anyone else feel like they were born 300 years too soon?"

A BUBBLE IN SPACE AND TIME

There is no doubt that the universe is still far too vast for humans to traverse. It takes more than four years for a beam of light to reach Earth's nearest star Proxima Centauri. Even with the best available propulsion systems, it would take tens of thousands of years for a human to get there. One can always dream about establishing colonies in other star systems, but it is not a journey anyone is likely to undertake.

But perhaps one day it might be possible to reduce the travel time. There are many ideas about how to do that, from laser-accelerated solar sails to nuclear propulsion. But even with the aid of these technologies, you would not get too far in a human lifetime. The galaxy really is open only to those who travel as fast as light—or faster.

For that very reason, imaginative physicists have long been pondering the ultimate propulsion system: a bubble in space and time in which a spaceship could dash from sun to sun, just like the USS *Enterprise* did. This is research at the fringe of science: not necessarily wrong but spiced with a large pinch of optimism.

The fact that scientists are dealing with the idea at all today is thanks to a 1994 paper by Mexican theoretical physicist Miguel Alcubierre. At the time, Alcubierre was not just a passionate *Star Trek* devotee. In his doctoral thesis at the University of Wales College Cardiff (now Cardiff University), Alcubierre also worked on the theory of relativity. Strictly speaking, the theory states that nothing can travel faster than light. But by applying a little creativity, Alcubierre identified an apparent loophole.

For physicists, Albert Einstein's theory of relativity consists of two parts: The "special" theory of relativity, which dates from 1905, deals with the uniform motion of fast-as-light objects. Ten years later Einstein generalized these ideas for accelerating bodies. According to "general" relativity, the three spatial dimensions we are familiar with (up-down, left-right, front-back) are inseparable from time. Every mass deforms this spacetime.

According to Einstein's epic discovery, we live in four-dimensional "spacetime." Spacetime is not static. Like a tablecloth, it is deformed by massive objects. Everything that moves across the tablecloth (or through spacetime) can accelerate only up to the speed limit set by light. The tablecloth itself, on the other hand, can be deformed at any speed, as the universe itself shows in some situations.

At the instant of the big bang, for example, the original spacetime structure presumably expanded for a split second and did so much faster than any ray of light could travel. Even today, the expansion continues to drive extremely distant galaxies away at speeds faster than light, which means their light can no longer reach us.

Based on his discovery, Alcubierre surmised that it would only be a small step to a warp drive. If spacetime

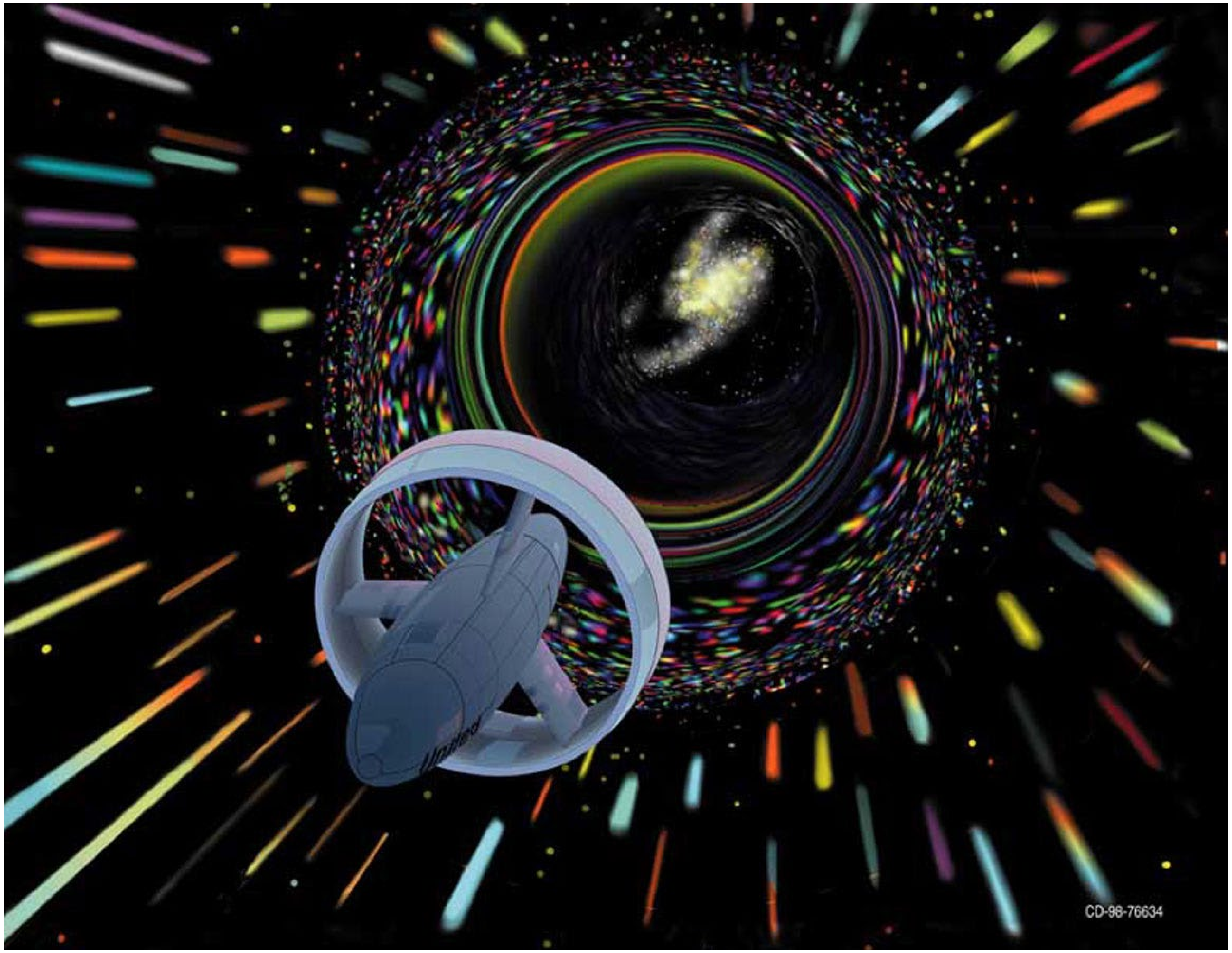
were contracted in front of a spaceship and expanded behind it to compensate, it would be possible to travel to one's destination at a speed faster than light. The ship would remain encapsulated in a bubble, and the crew would not sense the magnitude of the interstellar journey. In a 2017 lecture, Alcubierre compared it to being on a passenger conveyor belt at the airport: "You can imagine that the floor behind you is being created out of nothing and in front of you it is being destroyed, so you move along."

But formulating this idea in the language of general relativity immediately gives rise to major practical problems. First, to deform spacetime so radically, you would need to cram a huge mass into a bubble bounded by a wall thinner than an atomic nucleus. Then you would need two forms of matter to maintain the bubble. The gravity of ordinary mass would cause the space at the front of the bubble to contract, moving the whole structure forward. But at the same time, the space at the back of the bubble would need to expand like rising bread dough. To make that expansion happen, according to Alcubierre, you would need some form of negative energy radiating a kind of antigravity.

THE CURSE OF NEGATIVE ENERGY

For most physicists, that was the end of the thought experiment. Energy—which according to Einstein's formula $E = mc^2$ is equivalent to unconstrained mass—seems like it must, by definition, be positive. But according to quantum theory, it can indeed have a negative value. This seems to occur only in rare special cases, however—on a tiny scale. In the so-called Casimir effect, for example, the quantities involved are so minuscule that any technological application seems absurd.

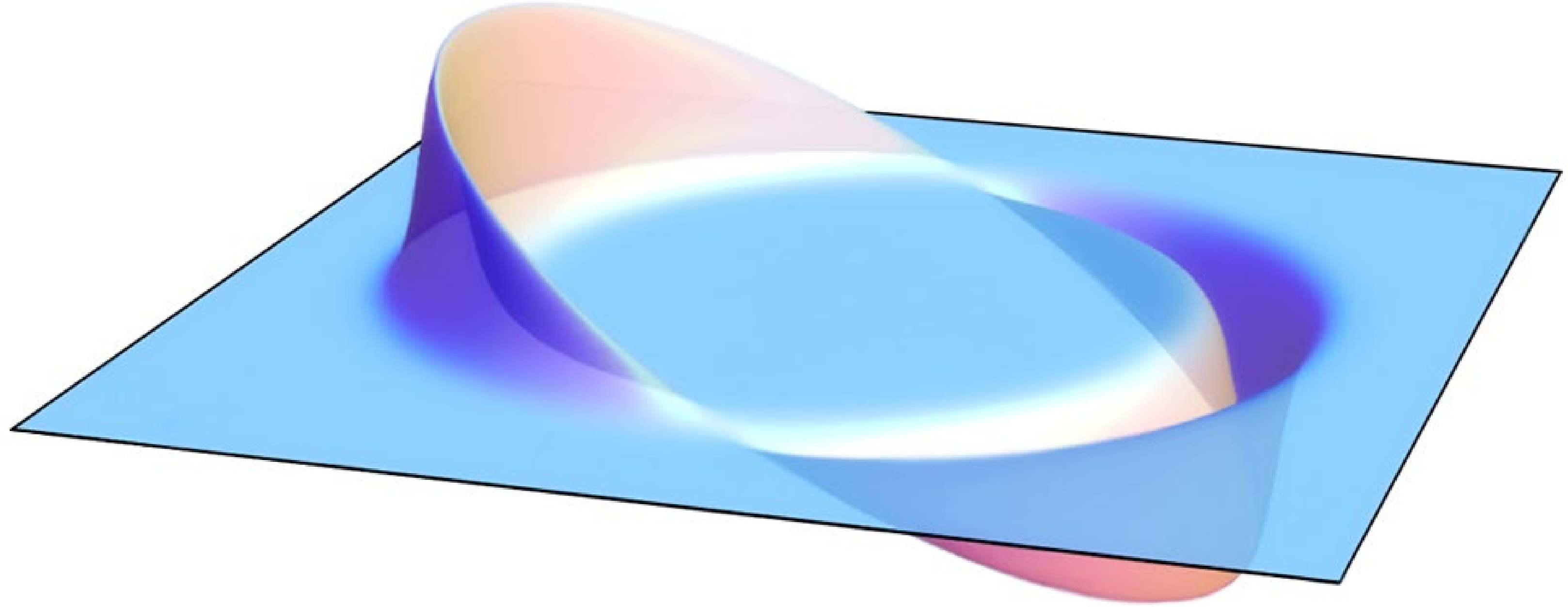
Alcubierre, now a professor of physics at the National Autonomous University of Mexico, concedes this point. In terms of a potential technology, warp drives "are greatly lacking," he and one of his colleagues wrote in a recent preprint paper. He has now turned his attention to known phenomena, such as black holes. The warp drive concept, however, retains its fascination, especially for Trekkies—and for a few gravitational physicists, who occasionally publish variations on the idea.



NASA artist's 1998 rendition of warp drive travel. The ring around the spacecraft generates a negative-energy field. From today's perspective, the negative-energy field would no longer be necessary.

NASA; Digital art by Les Bossinas (Cortez III Service Corp)

Some of these papers have shown how to reduce the bubble's mass requirements so that the total mass needed to deform spacetime would be less than that of our sun. But no one was able to get around the problem of negative energy—until Lentz took it up during the lockdown in Göttingen. In his enforced isolation, Lentz found a way to construct a warp bubble using only positive energy. In so



Principle of the Alcubierre drive: Spacetime contracts at the front of the bubble (*right*), corresponding to a warp in spacetime. Behind the bubble (*left*), new space is created out of nothing, which is equivalent to stretching spacetime.

doing, he may have overcome the greatest objection to warp drives.

What made it possible was a special feature of the geometry of spacetime that Lentz discovered buried in the general theory of relativity—more precisely, in Einstein's field equations. These equations can calculate how a particular distribution of matter and energy deforms spacetime. Researchers can also use them, as Alcubierre did, to determine the mass and energy needed to produce a specific curvature of space.

Dealing with a dynamic, four-dimensional structure like spacetime is extremely complicated, however. Writing out Einstein's formulas in full produces a jumble of nested differential equations with thousands of terms. Depending on the assumptions you make about a particular physical situation, you only take some of those terms into account. For theorists, it is an almost limitless playground.

Lentz specifically examined the assumptions leading to the negative energy requirements in Alcubierre's work. Like his colleague, Lentz began by analyzing spacetime, modeling the multidimensional substance as a stack of very thin layers. He found that Alcubierre had only considered comparatively simple "linear" relationships between the equations for shifting one layer onto the next. At this point, choosing more complex "hyperbolic" relations, which typically express rapidly changing quantities, results in a different warp bubble than the one obtained by Alcubierre. It still requires enormous amounts of mass and energy but, according to Lentz's calculations, only positive amounts. "I was very surprised that no one had tried this before me," Lentz says.

Lentz's bubble looks different from the one Alcubierre worked out in 1994. It consists of diamond-shaped regions of altered spacetime that resemble a flock of birds. Creating such a spacetime geometry in reality would involve a complicated layering of rings and disks, not made of solid material but of an extremely dense fluid of charged particles, similar to the substance found in the interior of neutron stars, Lentz says.

That means near-light-speed travel is still very, very far away from applied technology. But now that no exotic negative energy densities are needed—at least according to Lentz's latest work—the theoretical games are within the realm of established physics. Alcubierre describes Lentz's paper as a "very important development." Francisco Lobo, a researcher at the University of Lisbon and a colleague of Alcubierre's, who has published a textbook on warp drives, cannot find any obvious errors either. "If correct, this has the potential of opening up new interest and novel avenues of research in warp drive physics," he says.

Lentz's idea has even aroused interest among researchers outside the small community of warp drive enthusiasts, including Lavinia Heisenberg, a professor of cosmology at the Swiss Federal Institute of Technology Zurich. Heisenberg and her student Shaun Fell found Lentz's paper so exciting that they built on it by designing their own positive-energy warp bubbles that would require as little as a thousandth of the mass of our sun.

"The whole thing is much less mysterious than most people assume," says Alexey Bobrick, an astrophysicist at Lund University in Sweden. Collaborating with New York City–based entrepreneur Gianni Martire, Bobrick came up with some promising solutions to Einstein's field equations in 2020. According to Bobrick, all that is needed for a warp bubble is an appropriately shaped shell made of dense material that bends spacetime in its immediate vicinity while the universe through which the bubble moves and the space within the shell remain comparatively undisturbed.

TIME GOES BY SO SLOWLY

"Comparatively" is the key. Alcubierre and later warp architects assumed an abrupt transition between the contorted spacetime in the wall of the bubble and the smooth interior and exterior. But Bobrick and Martire found this "truncation" of the gravitational field to be

the reason why large amounts of negative energy are required to stabilize the contortion of space and time.

Abandoning the cartoonish image of a soap bubble, however, makes it possible to build warp drives based on ordinary matter, they claim. The gravitational field would not simply disappear when one moved away from the wall of the shell. Instead it would gradually decay. Spacetime would therefore also be curved inside the bubble. To travelers in a spaceship right in the middle of the bubble, this phenomenon would be most obvious in the passage of time: their watches would go slower than in the rest of space because, according to the theory of relativity, time is affected by gravity.

The slower passage of time on a spaceship might be something interstellar travelers appreciate. Still, Bobrick and Martire describe other obstacles. So far, they argue, there is no known way to actually accelerate a warp bubble. All previous ideas about the subject simply assume that the curvature of spacetime is already moving at high speed.

A beam of light travels 299,000 kilometers per second. According to Einstein's special theory of relativity, this is a physical constant. The speed of light is the maximum speed any particle may reach, and a particle can only do so if it has no mass. Consequently, today's physics offers no possibility of accelerating objects beyond the speed of light. On closer inspection, however, this limit only applies within the four-dimensional spacetime comprising the universe. Outside of that, even greater speeds appear to be possible.

"None of the physically conceivable warp drives can accelerate to speeds faster than light," Bobrick says. That is because you would require matter capable of being ejected at speeds faster than light—but no known particles can travel that fast. Furthermore, the bubble could not be controlled by occupants of the spaceship itself because they would lose contact with the outside world, owing to the extremely strong curvature of space around them.

"As long as one doesn't let personal biases get in the way and accepts what evidence tells you, it's a field of research that is as worthy of being pursued as any other."

—Erik Lentz

Lentz sees these objections as a problem, too, but he believes a solution can be found. Bobrick, meanwhile, points out that it is also possible to travel to distant stars at a third or half the speed of light, especially if time passes more slowly for the people in the warp bubble. Just do not think about the fact that all your relatives left behind on Earth will probably have died of old age before you get back. "But at least the idea is no longer completely crazy," Bobrick says.

FROM THEORY TO PRACTICE

There is still some debate about whether warp bubbles really can do without negative energy. Recently three theoreticians suggested that this claim was only true for observers moving next to the bubble. Plus, not everything that seems possible according to the theory of relativity actually exists—or is technologically feasible. For example, Einstein's field equations can also be used to justify "white" holes (the antithesis of their black hole counterparts), Einstein-Rosen bridges (frequently called wormholes) and other exotic alterations in spacetime that no one has ever observed. That could be because laws of nature, as yet unknown, preclude such phenomena.

Some researchers therefore caution against going overboard with the fantasies. Space propulsion expert Martin Tajmar of the Technical University of Dresden, for example, sees no practical relevance for the current work on warp drives. The huge masses involved simply exceed anything that can be tested on Earth, he says.

Most veteran warp drive researchers would undoubtedly agree. They see their work less as preparation for real-world experiments and more as a way of exploring the limits of relativity. In this endeavor, even speculative "thought experiments" are useful, Lobo says.

Lentz, on the other hand, is actively working toward a practical application of his idea. After his research in Göttingen, he took a job at an IT company. But in his spare time, he still thinks about how to accelerate a bend in spacetime to speeds faster than light and how to reduce the energy required to do so.

Lentz also advocates looking closely at the surroundings of neutron stars. It could be that these ultracompact stellar remnants eject bubbles like those that he describes in his paper. "As long as one doesn't let personal biases get in the way and accepts what evidence tells you, it's a field of research that is as worthy of being pursued as any other," he says.

Jean-Luc Picard would probably see it similarly. "Things are only impossible until they are not," the character noted in an episode of *Star Trek*: *The Next Generation*. But that's also easier to say when you live 300 years in the future. SA

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Future Space Travel Might Require Mushrooms

Mycologist Paul Stamets discusses the potential extraterrestrial uses of fungi, including terraforming planets, building human habitats–and providing psilocybin therapy to astronauts

By Nick Hilden

Trav Williams *Broken Banjo Photography*

Paul Stamets

Nick Hilden is a freelance writer whose work has appeared in the *Daily Beast*, *Men's Health*, *Thrillist*, *Salon*, the *Los Angeles Times*, and more. He's usually exploring some exciting corner of the world, and you can follow his writing and travels on Instagram @nick.hilden or Twitter @nickhilden

The list of mycologists whose names are known beyond their fungal field is short, and at its apex is Paul Stamets. Educated in, and a longtime resident of, the mossy, moldy, mushy Pacific Northwest region, Stamets has made numerous contributions over the past several decades—perhaps the best summation of which can be found in his 2005 book *Mycelium Running: How Mushrooms Can Help Save the World*. But now he is looking beyond Earth to discover new ways that mushrooms can help with the exploration of space.

In a new "astromycological" venture launched in conjunction with NASA, Stamets and various research teams are studying how fungi can be leveraged to build extraterrestrial habitats and perhaps someday even terraform planets. This is not the first time Stamets's career has intersected with speculative space science. He also recently received an honor that many researchers would consider only slightly less hallowed than a Nobel Prize: the distinction of having a *Star Trek* character named after him.

Scientific American spoke with Stamets about the out-of-this-world implications for the emerging field of astromycology.

[*An edited transcript of the interview follows.*]

***First, a chicken-or-egg question: Did* Star Trek: Discovery *name a character after you because you had started exploring astromycology, or was the idea for astromycology inspired by* Star Trek?**

CBS got ahold of me and said the writers of *Star Trek* wanted to talk to me: "We're in the dungeon, there's about a dozen of us, we've been tasked with *Star Trek: Discovery*, we're hitting a brick wall, and we saw your TED Talk." I had mentioned terraforming other planets with fungi.

What separates *Star Trek* from other science fiction, you know, is it really pioneered the importance of inclusivity, recognizing that the diversity of the members of our society gives us strength. And indeed, that's what I've learned as a mycologist: the biodiversity of our ecosystem gives our ecosystem resilience. Ultimately diversity wins.

So I told them terraforming with fungi on other planets is very plausible. Fungi were the first organisms that came to land, munching rocks, and fungi gave birth to animals about 650 million years ago. We're descendants of the descendants of these fungal networks.

I said, "You can have all these concepts for free. I'm a *Star Trek* fan; I don't want anything for this." I said, "But, you know, I always wanted to be the first astromycologist." And at the very end, they go, "Astromycologist, we love that! What a great phrase; we can use that."

How do you define the term "astromycology" here in our nonfictional universe?

Astromycology is obviously a subset of astrobiology, so astrobiology would be the study of biological organisms extraterrestrially.

Really, you're talking about the biology of the universe—and within the biology of the universe is our fungi. So astromycology would be the study of fungal biology throughout the universe. And I think it's inevitable we're going to someday find fungi on other planets.

How can Earth's fungi help with the development of human habitats or even entire ecosystems on other planets?

[Plants that support terraforming] need minerals, and pairing fungi up with the plants and debris from humans [causes them to] decompose into a form that then creates rich soils that could help generate the foods that astronauts need. It's much easier to take one seed and grow your food than it is to take a ton of food to space, right? Nature is incredibly efficient in terms of a payload. It's much better for nature to generate a payload of food than for your rocket to carry a payload of food.

Your current research proposal with NASA has two stages. The first involves identifying the best fungal species for breaking down asteroid regolith. Do you currently have any possible candidates?

Basically, regolith is asteroid dust. [Research teams] have constructed [synthetic] regolith that is supposed to mimic the components that are found on the surface of asteroids and also on Mars. So we're working with them now. I have a suite of about 700 strains of fungi in my cultural library. I made some recommendations, and I'm happy to say oyster mushrooms are one of the best ones that we've experimented with on the regolith so far.

And just recently we have found something synergistically that was unexpected when we took one species,

gave it a nutritional source, and we wanted to know how far it would grow into the regolith [with its mycelial roots]. When we took one species of fungi, and we looked at the reach that it had in the regolith, then we combined it with other species of fungi—each of which did not have that great of a reach. When we had a plurality of fungal species together, the outreach was far greater than anticipated. In some ways, it just proves this whole concept about biodiversity.

The second stage of your proposal involves determining the most effective way to use a fungus once the best type is selected. What might that look like?

The universe is rich with hydrocarbons. What oyster mushrooms do really well is break down hydrocarbons and dismantle them and restructure them into fungal carbohydrates, into sugars. Sugars are an absolutely essential nutrient, of course, for practically all life forms that I know of on this planet. So the idea of using hydrocarbons as a feedstock for oyster mushrooms makes a lot of sense.

Now, you have these kind of start/stops. You can only go so far without other inputs of essential nutrients. So it's not like the fungi could just use hydrocarbons alone—they need a boost. That's where we have to supplement them. But once you begin to create this reaction, it becomes catalytic—that is, self-sustaining. The more you feed this catalytic reaction, the more biodiversity you have. Again, you are having other organisms grow and die. They become a resource that provides vitamins, other minerals, perhaps other decomposable organic compounds such as cellulose or lignin, which can fuel these fungi to grow even larger and then support more plants that create more cellulose. And then they die, and they decompose, and these lenses of mycelium—shallow, usually circular colonies of mycelium—then begin to grow out more and more. So you're creating a micro-oasis environment that may just be a speck. And then these things begin to elaborate. And as their communities become more diverse and complex, these lenses of life then begin to become larger oases. And when the oasis environment is large enough, then it can sustain humans.

In addition to generating healthy soil, there are teams investigating how fungi might be used to grow structures on other worlds. Could you tell me more about how this sort of so-called mycotecture might work?

We grow lots of reishi mycelium, for instance. We grow reishi blocks. We wanted to crush these blocks in order to turn them into soil or get other value-added products. So we dried out these reishi blocks, and we tried to crush them. But we couldn't crush them. You could saw them with a saw blade, but if you tried to hit them with a hammer or something, they just wouldn't break. So this great engineer built us a hydraulic stainless-steel press, and I had like 2,000 psi [pounds per square inch] in this press, and we gave it my reishi blocks, and it bent the stainless steel. Trying to compress it, it actually broke the machine. This thing will crush rocks all day long and could not crush mycelium.

They're so structurally strong. They're also good at retaining heat, so their insulation properties are phenomenal. Moreover, these could become batteries. You can have solar panels on a structure on Mars made of mycelium. (The entire mycelium is about 85 percent carbon, and studies have shown that porous carbon can be an excellent capacitor.) You could then pregrow these and arrange them on a form such that they become nanobatteries. And they could then not only insulate you from the cold on the Martian or asteroid surface, but the house itself becomes a giant battery for power because they're so rich in carbon fibers. So that, to me, is really cool.

What kind of timelines do you have in mind for all of this? Is this the sort of thing we might see applied a decade from now or in a century?

Tomorrow. It's happening now. I'm guessing it will be implemented in space within 10 to 20 years.

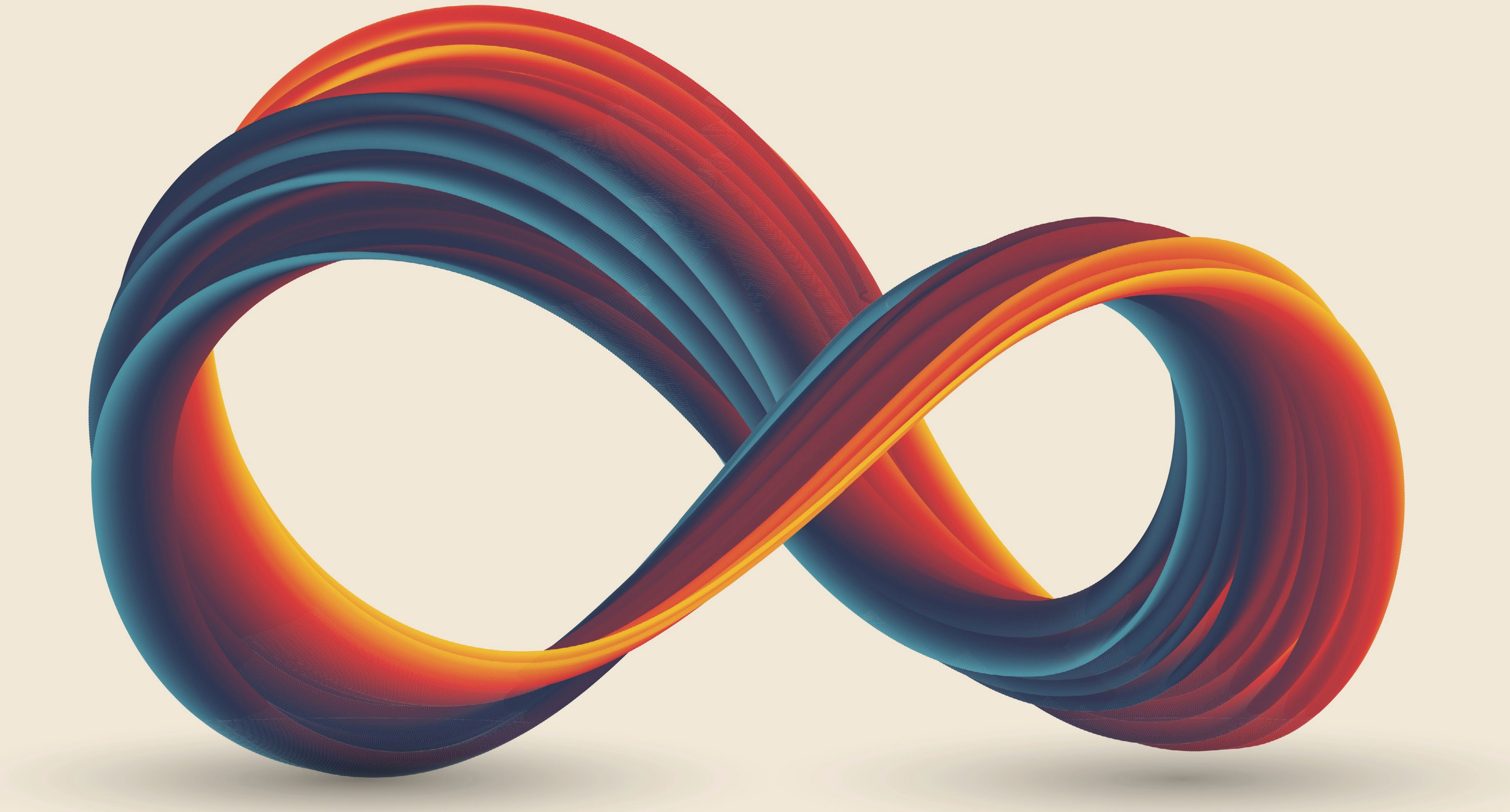
Before we wrap up, let's get a little more speculative. What are some of the more fantastic ways mushrooms might be applied in space?

Well, what I can tell you? I'm sure some of your editors may go, "No way, we're not going to publish this." But I think using psilocybin mushrooms in spaceflight makes a lot of sense. There are more than 65 articles right now … at ClinicalTrials.gov that say psilocybin mushrooms help people overcome [post-traumatic stress disorder], loneliness and depression. Do you think the astronauts are going to have loneliness and depression and PTSD? I think yes. How are you going to help them?

Under carefully controlled conditions, our astronauts [being] able to take psilocybin in space and look at the universe and not feel distant and alone but feel like they're part of this giant consciousness will give them a better frame of mind—psychologically, emotionally—to work with other astronauts and stay on mission. I feel that isolation, loneliness and depression are going to be major issues that astronauts face.

So I say this with great sincerity: NASA and anyone else working and looking at the settlement of space, you should consider that psilocybin mushrooms should be an essential part of your psychological tool kit for astronauts to be able to endure the solitude and the challenges of space and isolation.

Psilocybin mushrooms build creativity; people who are more creative come up with more solutions. I think that, in a sense, is a fertile ecosystem that can lead to the sustainability of humans in space. SA



A Deep Math Dive into Why Some Infinities Are Bigger Than Others

The size of certain infinite sets has been a mystery. Now, it turns out, each one is different than the next, and they can all be ordered by size

By Martin Goldstern and Jakob Kellner

Lidiia Moor *Getty Images*

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SIMPLE MATHEMATICAL CONCEPTS SUCH AS counting appear to be firmly anchored in the natural process of thinking. Studies have shown that even very young children and animals possess such skills to a certain extent. This is hardly surprising because counting is extremely useful in terms of evolution. For example, it is required for even very simple forms of trading. And counting helps in estimating the size of a hostile group and, accordingly, whether it is better to attack or retreat.

Over the past millennia, humans have developed a remarkable notion of counting. Originally applied to a handful of objects, it was easily extended to vastly different orders of magnitude. Soon a mathematical framework emerged that could be used to describe huge quantities, such as the distance between galaxies or the number of elementary particles in the universe, as well as barely conceivable distances in the microcosm, between atoms or quarks.

We can even work with numbers that go beyond anything currently known to be relevant in describing the universe. For example, the number $10^{10^{100}}$ (one followed by 10^{100} zeros, with 10^{100} representing one followed by 100 zeros) can be written down and used in all kinds of calculations. Writing this number in ordinary decimal notation, however, would require more elementary particles than are probably contained in the universe, even employing just one particle per digit. Physicists estimate that our cosmos contains fewer than 10^{100} particles.

Yet even such unimaginably large numbers are vanishingly small, compared with infinite sets, which have played an important role in mathematics for more than 100 years. Simply counting objects gives rise to the set of natural numbers, $\mathbb{N} = \{0, 1, 2, 3, \ldots\}$, which many of us encounter in school. Yet even this seemingly simple concept poses a challenge: there is no largest natural number. If you keep counting, you will always be able to find a larger number.

Can there actually be such a thing as an infinite set? In the 19th century, this question was very controversial. In philosophy, this may still be the case. But in modern mathematics, the existence of infinite sets is simply assumed to be true—postulated as an axiom that does not require proof.

Set theory is about more than describing sets. Just as, in arithmetic, you learn to apply arithmetical operations to numbers—for example, addition or multiplication—you can also define set-theoretical operations that generate new sets from given ones. You can take unions—$\{1, 2\}$ and $\{2, 3, 4\}$ becomes $\{1, 2, 3, 4\}$—or intersections—$\{1, 2\}$ and $\{2, 3, 4\}$ becomes $\{2\}$. More excitingly, you can form power sets—the family of all subsets of a set.

COMPARING SET SIZES

The power set $P(X)$ of a set X can be easily calculated for small X. For instance, $\{1, 2\}$ gives you $P(\{1,2\}) = \{\{\}, \{1\}, \{2\}, \{1, 2\}\}$. But $P(X)$ grows rapidly for larger X. For example, every 10-element set has $2^{10} = 1{,}024$ subsets. If you really want to challenge your imagination, try forming the power set of an infinite set. For example, the power set of the natural numbers, $P(\mathbb{N})$, contains the empty set, $\mathbb{N}$ itself, the set of all even numbers, the prime numbers, the set of all numbers with the sum of digits totaling 2021, $\{12, 17\}$, and much, much more. As it turns out, the number of elements of this power set exceeds the number of elements in the set of natural numbers.

To understand what that means, you first have to understand how the size of sets is defined. For the finite case, you can count the respective elements. For instance, $\{1,2,3\}$ and {Cantor, Gödel, Cohen} are of the same size. If you wish to compare sets with numerous (but finitely many) elements, there are two well-established methods. One possibility is to count the objects contained in each set and compare the numbers. Sometimes, however, it is easier to match the elements of one set to another. Then two sets are of the same size if and only if each element of one set can be uniquely paired with an element of the other set (in our example: 1 → Cantor, 2 → Gödel, 3 → Cohen).

This pairing method also works for infinite sets. Here, instead of first counting and then deriving concepts such as "greater than" or "equal to," you follow a reverse strategy. You start with defining what it means that two sets, A and B, are of the same size—namely, there is a mapping that pairs each element of A with exactly one element of B (so that no element of B is left over). Such a mapping is called bijection.

Similarly, A is defined to be less than or equal to B if there is a mapping from A to B that uses each element of B once at most.

After we have these notions, the size of sets is denoted by cardinal numbers, or cardinals. For finite sets, these

are the usual natural numbers. But for infinite sets, they are abstract quantities that just capture the notion of "size." For example, "countable" is the cardinal number of the natural numbers (and therefore of every set that has the same size as the natural numbers). It turns out that there are different cardinals. That is, there are infinite sets A and B with no bijection between them.

At first sight, this definition of size seems to lead to contradictions, which were elaborated by Bohemian mathematician Bernard Bolzano in *Paradoxes of the Infinite*, published posthumously in 1851. For example, Euclid's "The whole is greater than the part" appears self-evident. That means if a set A is a proper subset of B (that is, every element of A is in B, but B contains additional elements), then A must be smaller than B. This assertion is not true for infinite sets, however! This curious property is one reason some scholars rejected the concept of infinite sets more than 100 years ago.

For example, the set of even numbers E = {0, 2, 4, 6, ...} is a proper subset of the natural numbers N = {0,1,2, ...}. Intuitively, you might think that the set E is half the size of N. But in fact, based on our definition, the sets have the same size because each number n in E can be assigned to exactly one number in $\mathbb{N}$ ($0 \to 0$, $2 \to 1$, $4 \to 2$, ..., $n \to n/2$, ...).

Consequently, the concept of "size" for sets could be dismissed as nonsensical. Alternatively, it could be termed something else: cardinality, for example. For the sake of simplicity, we will stick to the conventional terminology, even though it has unexpected consequences at infinity.

In the late 1800s German logician Georg Cantor, founder of modern set theory, discovered that not all infinite sets are equal. According to his proof, the power set $P(X)$ of a (finite or infinite) set X is always larger than X itself. Among other things, it follows that there is no largest infinity and thus no "set of all sets."

AN UNRESOLVED HYPOTHESIS

There is, however, something akin to a smallest infinity: all infinite sets are greater than or equal to the natural numbers. Sets X that have the same size as $\mathbb{N}$ (with a bijection between $\mathbb{N}$ and X) are called countable; their cardinality is denoted $\aleph_0$, or aleph null. For every infinite cardinal $\aleph_a$, there is a next larger cardinal number $\aleph_{a+1}$. Thus, the smallest infinite cardinal $\aleph_0$ is followed by $\aleph_1$, then $\aleph_2$ and so on. The set $\mathbb{R}$ of real numbers (also called the real line) is as large as the power set of $\mathbb{N}$, and this cardinality is denoted $2^{\aleph_0}$, or "continuum."

In the 1870s Cantor ruminated over whether the size of $\mathbb{R}$ was the smallest possible cardinal above $\aleph_0$—in other words, whether $\aleph_1 = 2^{\aleph_0}$. Previously, every infinite subset of $\mathbb{R}$ that had been studied had turned out to be either as large as $\mathbb{N}$ or $\mathbb{R}$ itself. This led Cantor to what is known as the continuum hypothesis (CH): the assertion that the size of $\mathbb{R}$ is the smallest possible uncountable cardinal. For decades, CH kept mathematicians busy, but a proof eluded them. Later, it became clear their efforts had been doomed from the start.

Set theory is extremely powerful. It can describe virtually all mathematical concepts. But it also has limitations. The field is based on the axiomatic system formulated more than 100 years ago by German logician Ernst Zermelo and elaborated by his German-Israeli colleague Abraham Fraenkel. Called ZFC, or Zermelo-Fraenkel set theory (C stands for "axiom of choice"), the system is a collection of basic assumptions sufficient to carry out almost all of mathematics. Very few problems require additional assumptions. But in 1931 Austrian mathematician Kurt Gödel recognized that the system has a fundamental defect: it is incomplete. That is, it is possible to formulate mathematical statements that can neither be refuted nor proved using ZFC. Among other things, it is impossible for a system to prove its own consistency.

The most famous example of undecidability in set theory is CH. In a paper published in 1938, Gödel proved that CH cannot be disproved within ZFC. Neither can it be proved, as Paul Cohen showed 25 years later. It is thus impossible to solve CH using the usual axioms of set theory. Consequently, it remains unclear whether sets exist that are both larger than the natural numbers and smaller than the real numbers.

Cardinality is not the only notion to describe the size of a set. For example, from the point of view of geometry, subsets of the real line R, the two-dimensional plane (sometimes called the x-y plane) or the three-dimensional space can be assigned length, area or volume. A set of points in the plane forming a rectangle with side lengths a and b has an area of $a \cdot b$. Calculating the area of more complicated subsets of the plane sometimes requires other tools, such as the integral calculus taught in school. This method does not suffice for certain complex sets. But many can still be quantified using the Lebesgue measure, a function that assigns length, area or volume to extremely complicated objects. Even so, it is possible to define subsets of $\mathbb{R}$, or the plane, that are so frayed that they cannot be measured at all.

In two-dimensional space, a line (such as the circumference of a circle, a finite segment or a straight line) is always measurable, and its area is zero. It is therefore called a null set. Null sets can also be defined in one dimension. On the real line, the set with two elements—for example $\{3, 5\}$—has a measure zero, whereas an interval such as $[3, 5]$—that is, the real numbers between three and five—has a measure two.

NEGLIGIBLE SETS

The concept of a null set is extremely useful in mathematics. Often a theorem is not true for all real numbers but can be proved for all real numbers outside of a null set. This is usually good enough for most applications. Yet null sets may seem quite large. For example, the rational num-

bers within the real line are a null set even though there are infinitely many of them. This is because any countable—or finite—set is a null set. The converse is not true: a subset of the x-y plane with a large cardinality need be neither measurable nor of large measure. For example, the entire plane with its $2^{\aleph_0}$ elements has an infinite measure. But the x axis with the same cardinality has a two-dimensional measure (or "area") zero and thus is a null set of the plane.

Such "negligible" sets led to fundamental questions about the size of 10 infinite cardinals, which remained unanswered for a long time. For example, mathematicians wished to know the minimum size a set must have for it not to be a null set. The family of all null sets is denoted by $\mathcal{N}$, and the smallest cardinality of a non-null set is denoted by non($\mathcal{N}$). It follows that $\aleph_0 <$ non($\mathcal{N}$) $\leq 2^{\aleph_0}$, because any set of size $\aleph_0$ is a null set, and the whole plane has size $2^{\aleph_0}$ and is not a null set. Thus, $\aleph_1 \leq$ non($\mathcal{N}$) $\leq 2^{\aleph_0}$, because $\aleph_1$ is the smallest uncountable cardinal. If we assume CH, then non($\mathcal{N}$) $= 2^{\aleph_0}$, because, in that case, $\aleph_1 = 2^{\aleph_0}$.

We can define another cardinal number, add($\mathcal{N}$), to answer the question, What is the minimal number of null sets whose union is a non-null set? This number is less than or equal to non($\mathcal{N}$): if A is a non-null set containing non($\mathcal{N}$) many elements, the union of all the non($\mathcal{N}$) many one-element subsets of A is the non-null set A. But a smaller number of null sets (though they would not be one-element sets) could also satisfy the requirements. Therefore, add($\mathcal{N}$) $\leq$ non($\mathcal{N}$) holds.

The cardinal cov($\mathcal{N}$) is the smallest number of null sets whose union yields the whole plane. It is also easy to see that add($\mathcal{N}$) is smaller than or equal to cov($\mathcal{N}$) because, as already mentioned, the plane is a non-null set.

We can also consider cof($\mathcal{N}$), the smallest possible size for a basis X of $\mathcal{N}$. That is, a set X of null sets that contains a superset B of every null set A. (That means A is a subset of B.) These infinite cardinals—add($\mathcal{N}$), cov($\mathcal{N}$), non($\mathcal{N}$) and cof($\mathcal{N}$)—are important characteristics of the family of null sets.

For each of these four cardinal characteristics, an analogous characteristic can be defined using a different concept of small, or negligible, sets. This other notion of smallness is "meager." A meager set is a set contained in the countable union of nowhere dense sets, such as the circumference of a circle in the plane, or finitely or countably many such circumferences. In one dimension, the normal numbers form a meager set on the real line, while the remaining reals, the non-normal numbers, constitute a null set.

Accordingly, the corresponding cardinal characteristics can be defined for the family of meager sets: add($\mathcal{M}$), non($\mathcal{M}$), cov($\mathcal{M}$) and cof($\mathcal{M}$). Under CH, all characteristics are the same, namely $\aleph_1$, for both null and meager sets. On the other hand, using the method of "forcing," developed by Cohen, mathematicians Kenneth Kunen and Arnold Miller were able to show in 1981 that it is impossible to prove the statement add($\mathcal{N}$) = add($\mathcal{M}$) within ZFC. In other words, the numbers of null and meager sets that must be combined to produce a non-negligible set are not provably equal.

Forcing is a method to construct mathematical universes. A mathematical universe is a model that satisfies the ZFC axioms. To show that a statement X is not refutable in ZFC, it is enough to find a universe in which both ZFC and X are valid. Similarly, to show that X is not provable from ZFC, it is enough to find a universe where ZFC holds, but X fails.

MATHEMATICAL UNIVERSES WITH SURPRISING PROPERTIES

Kunen and Miller used this method to construct a mathematical universe that satisfies add($\mathcal{N}$) < add($\mathcal{M}$). In this model, more meager than null sets are required to form a nonnegligible set. Accordingly, it is impossible to prove add($\mathcal{N}$) $\geq$ add($\mathcal{M}$) from ZFC.

In contrast, Tomek Bartoszynski discovered three years later that the converse inequality add($\mathcal{N}$) $\leq$ add($\mathcal{M}$) can be proved using ZFC. This points to an asymmetry between the two notions of smallness. Let us note that this asymmetry is not visible if we assume CH because CH implies $\aleph_1$ = add($\mathcal{N}$) = add($\mathcal{M}$).

To summarize: add($\mathcal{N}$) $\leq$ add($\mathcal{M}$) is provable, but neither add($\mathcal{N}$) = add($\mathcal{M}$) nor add($\mathcal{N}$) < add($\mathcal{M}$) is provable. This is the same effect as with CH: it is trivial to prove that $\aleph_1 \leq 2^{\aleph_0}$, but neither $\aleph_1 < 2^{\aleph_0}$ nor $\aleph_1 = 2^{\aleph_0}$ is provable.

In addition to the cardinal numbers defined so far, there are two important cardinal characteristics—$\mathfrak{b}$ and $\mathfrak{d}$—that refer to dominating functions of real numbers. For two continuous functions (of which there are $2^{\aleph_0}$ many) f and g, f is said to be dominated by g if the inequality $f(x) < g(x)$ holds for all sufficiently large x. For example, a quadratic function such as $g(x) = x^2$ always dominates a linear function, say $f(x) = 100x + 30$.

The cardinal number $\mathfrak{d}$ is defined as the smallest possible size of a set of continuous functions sufficient to dominate every possible continuous function.

A variant of this definition gives the cardinal number $\mathfrak{b}$, namely, the smallest size of a family B with the property that there is no continuous function that dominates all functions of B. It can be shown that $\aleph_1 \leq \mathfrak{b} \leq \mathfrak{d} \leq 2^{\aleph_0}$ holds.

Several additional inequalities have been shown to hold between the 12 infinite cardinals we just defined. All these inequalities are summarized in Cichoń's diagram, introduced by British mathematician David Fremlin in 1984 and named after his Polish colleague Jacek Cichoń. For typographical reasons, the less-or-equal signs are replaced by arrows.

There are two additional relations: Add($\mathcal{M}$) is the smaller one of $\mathfrak{b}$ and cov($\mathcal{M}$). Likewise, cof($\mathcal{M}$) is the larger of $\mathfrak{d}$ and non($\mathcal{M}$). These two "dependent" cardinals are marked with a frame in the Cichoń diagram. The

$$
\begin{tikzcd}
& \mathrm{cov}(\mathcal{N}) \arrow[r] & \mathrm{non}(\mathcal{M}) \arrow[r] & \boxed{\mathrm{cof}(\mathcal{M})} \arrow[r] & \mathrm{cof}(\mathcal{N}) \arrow[r] & 2^{\aleph_0} \\
& & \mathfrak{b} \arrow[u] \arrow[r] & \mathfrak{d} \arrow[u] & & \\
\aleph_1 \arrow[r] & \mathrm{add}(\mathcal{N}) \arrow[uu] \arrow[r] & \boxed{\mathrm{add}(\mathcal{M})} \arrow[u] \arrow[r] & \mathrm{cov}(\mathcal{M}) \arrow[u] \arrow[r] & \mathrm{non}(\mathcal{N}) \arrow[uu] &
\end{tikzcd}
$$

diagram thus comprises 12 uncountable cardinalities of which no more than 10 can be simultaneously different.

HOW DIFFERENT CAN INFINITIES BE?

If CH holds, however, $\aleph_1$ (the smallest number in the diagram) is equal to $2^{\aleph_0}$ (the largest number in the diagram), and thus all entries are equal. If, on the other hand, we assume CH to be false, then they could be quite different.

For several decades, mathematicians tried to show that none of the less-or-equal relations in Cichoń's diagram can be strengthened to equalities. To do that, they constructed many different universes in which they assigned the two smallest uncountable cardinals, $\aleph_1$ and $\aleph_2$, to the entries of the diagram in various ways. For example, they created a universe for which $\aleph_1 = \mathrm{add}(\mathcal{N}) = \mathrm{cov}(\mathcal{N})$ and $\aleph_2 = \mathrm{non}(\mathcal{M}) = \mathrm{cof}(\mathcal{M})$.

This work enabled researchers in the 1980s to confirm that for all pairs of cardinals, only the relationships indicated in the diagram can be proved in ZFC. More precisely, for every labeling of the (independent) Cichoń diagram entries with the values $\aleph_1$ and $\aleph_2$ that honors the inequalities of the diagram, there is a universe that realizes the given labeling.

So we have known for nearly four decades that all assignments of $\aleph_1$ and $\aleph_2$ to the diagram are possible. But what can we say for more than two values? Could, for example, all the independent entries be simultaneously different? Some cases with three characteristics have been known for 50 years, and in the 2010s more universes were discovered (or constructed) in which up to seven different cardinals appeared in the Cichoń diagram.

In a 2019 paper we constructed with Israeli mathematician Saharon Shelah of the Hebrew University of Jerusalem, a universe in which the maximum possible number of different infinite values—10, that is—appears in Cichoń's diagram. In doing so, however, we used a stronger system of axioms than ZFC, one that assumes the existence of "large cardinals," infinities whose existence is not provable in ZFC alone.

While we were very pleased with this result, we were not entirely satisfied. We worked for two more years to find a solution using only the ZFC axioms. Together with Shelah and Colombian mathematician Diego Mejía of Shizuoka University in Japan, we finally succeeded in proving the result without these additional assumptions.

We have thus shown that the 10 characteristics of the real numbers can all be different. Let us note that we did not show that there can be at least, at most or precisely 10 infinite cardinals between $\aleph_1$ and the continuum. This was already proved by Robert Solovay in 1963. In fact, the size of the set of real numbers can vary greatly: there could be eight, 27 or infinitely many cardinal numbers between $\aleph_1$ and $2^{\aleph_0}$—even uncountably many. Rather our result proves that there are mathematical universes in which the 10 specific cardinal numbers between $\aleph_1$ and $2^{\aleph_0}$ turn out to be different.

This is not the end of the story. As is usual for mathematics, many questions remain open, and new ones arise. For example, in addition to the cardinal numbers described here, many other infinite cardinalities lying between $\aleph_1$ and the continuum have been discovered since the 1940s. Their precise relationships to one another are unknown. To distinguish some of these characteristics in addition to those in Cichoń's diagram is one of the upcoming challenges. Another one is to show that other orderings of 10 different values are possible. Unlike in the case for the two values $\aleph_1$ and $\aleph_2$, where we know that all possible orders are consistent, in the case of all 10 values, we could only show the consistency of two different orderings. So, who knows, there may still be hitherto undiscovered equalities—involving more than two characteristics—hidden in the diagram. SA

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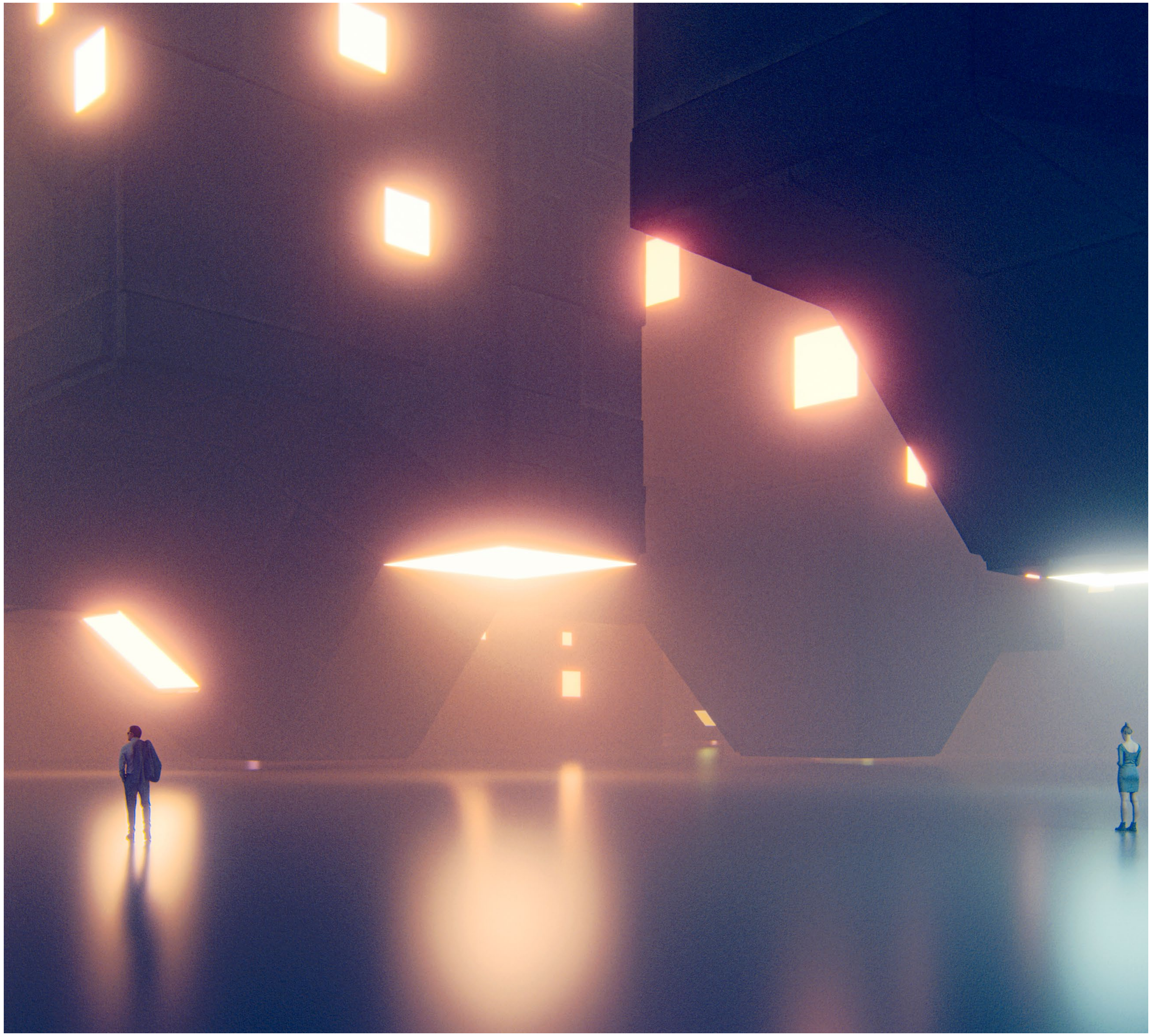
BEHAVIOR

What God, Quantum Mechanics and Consciousness Have in Common

Theories that try to explain these big metaphysical mysteries fall short, making agnosticism the only sensible stancee



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In my 20s, I had a friend who was brilliant, charming, Ivy-educated and rich, heir to a family fortune. I'll call him Gallagher. He could do anything he wanted. He experimented, dabbling in neuroscience, law, philosophy and other fields. But he was so critical, so picky, that he never settled on a career. Nothing was good enough for him. He never found love for the same reason. He also disparaged his friends' choices, so much so that he alienated us. He ended up bitter and alone. At least that's my guess. I haven't spoken to Gallagher in decades.

There is such a thing as being too picky, especially when it comes to things like work, love and

nourishment (even the pickiest eater has to eat something). That's the lesson I gleaned from Gallagher. But when it comes to answers to big mysteries, most of us aren't picky enough. We settle on answers for bad reasons, for example, because our parents, priests or professors believe them. We think we need to believe something, but actually we don't. We can, and should, decide that no answers are good enough. We should be agnostics.

Some people confuse agnosticism (not knowing) with apathy (not caring). Take Francis Collins, a geneticist who directs the National Institutes of Health. He is a devout Christian who believes that Jesus performed miracles, died for our sins and rose from the dead. In his 2006 best seller *The Language of God,* Collins calls agnosticism a "cop-out." When I interviewed him, I told him I am an agnostic and objected to "cop-out."

Collins apologized. "That was a put-down that should not apply to earnest agnostics who have considered the evidence and still don't find an answer," he said. "I was reacting to the agnosticism I see in the scientific community, which has not been arrived at by a careful examination of the evidence." I have examined the evidence for Christianity, and I find it unconvincing. I'm not convinced by any scientific creation stories, either, such as those that depict our cosmos as a bubble in an oceanic "multiverse."

People I admire fault me for being too skeptical. One is the late religious philosopher Huston Smith, who called me "convictionally impaired." Another is megapundit Robert Wright, an old friend, with whom I've often argued about evolutionary psychology and Buddhism. Wright once asked me in." People I admire fault me for being too skeptical. One is the late religious philosopher Huston Smith, who called me "convictionally impaired." Another is megapundit Robert Wright, an old friend, with whom I've often argued about evolutionary psychology and Buddhism. Wright once asked me in exasperation, "Don't you believe anything?" Actually, I believe lots of things, for example, that war is bad and should be abolished.

But when it comes to theories about ultimate reality, I'm with Voltaire. "Doubt is not a pleasant condition," Voltaire said, "but certainty is an absurd one." Doubt protects us from dogmatism, which can easily morph into fanaticism and what William James calls a "premature closing of our accounts with reality." Below I defend agnosticism as a stance toward the existence of God, interpretations of quantum mechanics and theories of consciousness. When considering alleged answers to these three riddles, we should be as picky as my old friend Gallagher.

THE PROBLEM OF EVIL

Why do we exist? The answer, according to the major monotheistic religions, including the Catholic faith in which I was raised, is that an all-powerful, supernatural entity created us. This deity loves us, as a human father loves his children, and wants us to behave in a certain way. If we're good, He'll reward us. If we're bad, He'll punish us. (I use the pronoun "He" because most scriptures describe God as male.)

My main objection to this explanation of reality is the problem of evil. A casual glance at human history, and at the world today, reveals enormous suffering and injustice. If God loves us and is omnipotent, why is life so horrific for so many people? A standard response to this question is that God gave us free will; we can choose to be bad as well as good.

The late, great physicist Steven Weinberg, an atheist, who died in July, slaps down the free will argument in his book *Dreams of a Final Theory*. Noting that Nazis killed many of his relatives in the Holocaust, Weinberg asks: Did millions of Jews have to die so the Nazis could exercise their free will? That doesn't seem fair. And what about kids who get cancer? Are we supposed to think that cancer cells have free will?

On the other hand, life isn't always hellish. We experience love, friendship, adventure and heartbreaking beauty. Could all this really come from random collisions of particles? Even Weinberg concedes that life sometimes seems "more beautiful than strictly necessary." If the problem of evil prevents me from believing in a loving God, then the problem of beauty keeps me from being an atheist like Weinberg. Hence, agnosticism.

THE PROBLEM OF INFORMATION

Quantum mechanics is science's most precise, powerful theory of reality. It has predicted countless experiments, spawned countless applications. The trouble is, physicists and philosophers disagree over what it means, that is, what it says about how the world works. Many physicists—

most, probably—adhere to the Copenhagen interpretation, advanced by Danish physicist Niels Bohr. But that is a kind of anti-interpretation, which says physicists should not try to make sense of quantum mechanics; they should "shut up and calculate," as physicist David Mermin once put it.

Philosopher Tim Maudlin deplores this situation. In his 2019 book *Philosophy of Physics: Quantum Theory,* he points out that several interpretations of quantum mechanics describe in detail how the world works. These include the GRW model proposed by Ghirardi, Rimini and Weber; the pilot-wave theory of David Bohm; and the many-worlds hypothesis of Hugh Everett. But here's the irony: Maudlin is so scrupulous in pointing out the flaws of these interpretations that he reinforces my skepticism. They all seem hopelessly kludgy and preposterous.

Maudlin does not examine interpretations that recast quantum mechanics as a theory about information. For positive perspectives on information-based interpretations, check out *Beyond Weird* by journalist Philip Ball and *The Ascent of Information* by astrobiologist Caleb Scharf. But to my mind, information-based takes on quantum mechanics are even less plausible than the interpretations that Maudlin scrutinizes. The concept of information makes no sense without conscious beings to send, receive and act on the information.

Introducing consciousness into physics undermines its claim to objectivity. Moreover, as far as we know, consciousness arises only in certain organisms that have existed for a brief period here on Earth. So how can quantum mechanics, if it's a theory of information rather than matter and energy, apply to the entire cosmos since the big bang? Information-based theories of physics seem like a throwback to geocentrism, which assumed the universe revolves around us. Given the problems with all interpretations of quantum mechanics, agnosticism, again, strikes me as a sensible stance.

MIND-BODY PROBLEMS

The debate over consciousness is even more fractious than the debate over quantum mechanics. How does matter make a mind? A few decades ago a consensus seemed to be emerging. Philosopher Daniel Dennett, in his cockily entitled book *Consciousness Explained,* asserted that consciousness clearly emerges from neural processes, such as electrochemical pulses in the brain. Francis Crick and Christof Koch proposed that consciousness is generated by networks of neurons oscillating in synchrony.

Gradually, this consensus collapsed, as empirical evidence for neural theories of consciousness failed to materialize. As I point out in my recent book *Mind-Body Problems,* there are now a dizzying variety of theories of consciousness. Koch has thrown his weight behind integrated information theory, which holds that consciousness might be a property of all matter, not just brains. This theory suffers from the same problems as information-based theories of quantum mechanics. Theorists such as Roger Penrose, who won last year's Nobel Prize in Physics, have conjectured that quantum effects underpin consciousness, but this theory is even more lacking in evidence than integrated information theory.

Researchers cannot even agree on what form a theory of consciousness should take. Should it be a philosophical treatise? A purely mathematical model? A gigantic algorithm, perhaps based on Bayesian computation? Should it borrow concepts from Buddhism, such as anatta, the doctrine of no self? All of the above? None of the above? Consensus seems farther away than ever. And that's a good thing. We should be open-minded about our minds.

So, what's the difference, if any, between me and Gallagher, my former friend? I like to think it's a matter of style. Gallagher scorned the choices of others. He resembled one of those mean-spirited atheists who revile the faithful for their beliefs. I try not to be dogmatic in my disbelief, and to be sympathetic toward those who, like Collins, have found answers that work for them. Also, I get a kick out of inventive theories of everything, such as John Wheeler's "it from bit" and Freeman Dyson's principle of maximum diversity, even if I can't embrace them.

I'm definitely a skeptic. I doubt we'll ever know whether God exists, what quantum mechanics means, how matter makes mind. These three puzzles, I suspect, are different aspects of a single, impenetrable mystery at the heart of things. But one of the pleasures of agnosticism—perhaps the greatest pleasure—is that I can keep looking for answers and hoping that a revelation awaits just over the horizon.

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ASTRONOMY

Astronomer Vera Rubin Taught Me about Dark Matter–and about How to Live Life

The groundbreaking scientist ushered in a revolution in how we think about the universe. She also lived by a set of principles that made her an exceptional human being

Rubin at her office at the Carnegie Institution of Washington in 2010, at the age of 82.

Linda Davidson *Getty Images*

"Could I come to the telescope with you?" I innocently asked the late astronomer Vera Rubin that question a few weeks after I met her in 2007.

Even then, in her late 70s, Rubin continued her trips to places such as Kitt Peak National Observatory to scour the outermost edges of far-flung galaxies in order to clock how quickly the galaxies' stars whipped around their cores. In our solar system, Mercury whips around the sun at high velocity, while Pluto merely plods along, and astronomers naturally assumed that stars close to a galaxy's core would similarly move faster than stars out at the edge.

Yet years of work with her collaborator Kent Ford and other colleagues had revealed that this isn't true; the stars farthest out tend to move just as swiftly as stars closer in. In the 1960s and 1970s this observation shocked scientists. It implied that the gravity from some invisible form of matter was making the outermost stars move unexpectedly quickly—and that there was vastly more matter in the cosmos that astronomers originally thought. It meant, as Rubin so adeptly noted in 1985, the universe had been playing a trick on us, keeping the majority of the universe's matter hidden from view.

I had not known about the universe's trick until I came across a description of Rubin's research while interning at the National Air and Space Museum in Washington, D.C., and wandering around the Explore the Universe exhibit. Reading about Rubin, my brain buzzed. Who was she?

Why hadn't I heard more about her? Did we really not know what most of the universe was made of? I peppered my supervisor, David DeVorkin, with these questions and others. He pointed me to Rubin's collection of essays, *Bright Galaxies, Dark Matters*. A day later he asked: "Would like you to interview Vera?"

Absolutely, yes, I said. DeVorkin was working on Rubin's oral history, which he wanted to finish. I read and researched, preparing questions. On the day of the interview, Rubin welcomed us into her office at the department of terrestrial magnetism, the same one she'd shared with Ford for decades. Dozens of stories and anecdotes later, we headed to Rubin's home not far from Chevy Chase, where both Vera and Robert Rubin, her husband, answered our questions. The couple finished each other's thoughts. They made each other laugh. In that afternoon, their mutual love and respect were obvious, even unspoken. That's the kind of relationship I want, I remember thinking.

Finding a partner who was patient, kind and as invested in your career as in their own, was advice Rubin often gave in talks and interviews. She not only said it. She lived it. She also showed me how to make others feel important. Even though I was a stranger, an intern, she listened to me. She asked me questions about my aspirations. She encouraged me. She didn't have to do that. She chose to.

Because I felt Rubin was so approachable, I dared to write and ask to go to the telescope with her. She thanked me for my "sweet letter," and in a September 20, 2007, e-mail wrote, "The answer is yes, but … telescope time is very valuable, and making mistakes is very easy." She told me when to arrive at the telescope, when to watch her work and when to ask questions. And then she said, "Bring a warm coat or jacket … we'll be observing in a warm room but have to go out to the telescope sometimes." She was open to my request, set boundaries and still looked out for my well-being. High expectations and warmth (no coat pun intended) again were traits I wanted to emulate.

On that crisp night in mid-November 2007, we met at Kitt Peak. That first night there, she flicked a switch, and the darkness of the telescope's dome swallowed her. She quickly and confidently took a few steps, grabbed the staircase railing and climbed up. At the top, she slid her hand across the door, found the knob and pushed. Nothing happened. Like a football lineman, she lowered her center of gravity and threw her weight against the hinged hunk of metal, bumping it open with her hip.

That scene became the opening of my book, *Bright Galaxies, Dark Matter and Beyond*, a tour of Rubin's life. In it, I try to convey her grace, wit and grit, even in the face of sexism and sometimes scorn for her research. I also explore the life lessons she taught me: Listen, speak up against injustice, be fearless and, above all, be curious.

"Each one of you can change the world," she wrote in *Bright Galaxies, Dark Matters*, "for you are made of star stuff, and you are connected to the universe."

Avi Loeb is former chair (2011–2020) of the astronomy department at Harvard University, founding director of Harvard's Black Hole Initiative, and director of the Institute for Theory and Computation at the Harvard-Smithsonian Center for Astrophysics. He also chairs the Board on Physics and Astronomy of the National Academies and the advisory board for the Breakthrough Starshot project and is a member of the President's Council of Advisors on Science and Technology. Loeb is the bestselling author of *Extraterrestrial: The First Sign of Intelligent Life Beyond Earth* (Houghton Mifflin Harcourt).

EXTRATERRESTRIAL LIFE

To Understand UAP, We Need Megapixel Imagery

If any of them represent advanced technology, high-resolution photographs might tell us whether they're metaphorically labeled "Made in China" or "Made on Exoplanet X"

Getty Images

The Pentagon report on unidentified aerial phenomena (UAP) that was delivered to Congress on June 25 is intriguing enough to motivate scientific inquiry toward the goal of what these phenomena are. The nature of UAP is not a philosophical matter. It's also not a puzzle that politicians should be asked to resolve—for the same reason that plumbers should not be asked to bake cakes. Policy makers or military personnel have insufficient training in science to solve this mystery, and hoping that they will somehow do so is like the frustrating experience of the characters in Samuel Beckett's play *Waiting for Godot*.

Given these circumstances, scientists should find the answer through the standard scientific process, based on a transparent analysis of open data. The task boils down to getting a high-resolution image of UAP. A picture is worth a thousand words. More specifically, a megapixel image of the surface of an unusual object will allow us to distinguish whether it bears the metaphorical label "Made in China" or "Made in Russia" from the alternative: "Made on Exoplanet X."

Consider an object the size of a person at a

distance of one mile. Suppose we wish to resolve features as small as the width of a letter in this text. That is equivalent to resolving a thousandth of the person's height, which would require obtaining a megapixel image. The Rayleigh criterion in optics implies that the best angular resolution of a telescope is at the so-called diffraction limit, roughly the wavelength of light divided by the aperture diameter. For visible light, the desired resolution in our example can be obtained by a telescope with a diameter of a meter, which can be purchased off-the-shelf online.

The telescope should be linked to a suitable camera, with the resulting data stream fed to a computer system—where optimized software would filter out the transients of interest as the telescope tiles the sky with its field of view. The initial survey could start from a large field of view but then zoom in on the object of interest as it is tracked across the sky. UAP could change their sky position much faster than any astronomical sources located at great distances.

But they also need to be distinguished from birds, airplanes, satellites or instrumental artifacts. The actual fidelity of the image will be limited by blurring because of atmospheric turbulence and will therefore depend on the elevation and distance of the UAP. The sky survey will also need to extend over a period long enough for the detection of UAP to be probable. These are all major challenges.

The telescope facilities can be placed in geographical locations that will maximize the chance of reproducing past UAP reports. Lower-cost video cameras with lower resolution can be distributed across more locations around the globe to achieve a comprehensive survey of the entire sky. There are astronomical facilities, such as ZTF, LCO, TAOS, ASASSN or PanSTARRS, already in place at remote locations for the different task of searching for transient objects that do not move across the sky as fast as UAP. The data volume will increase dramatically when the VRO/LSST facility in Chile commences operations in 2023. UAP debunkers often ask why cameras invariably capture fuzzy images of unidentified objects. The answer is simple: their apertures are hundreds of times smaller than the desired meter-scale telescopes.

The cost of establishing a network of suitable telescopes is lower than the amount invested so far in the search for the nature of dark matter. We do not know which particles constitute most of the matter in the universe. It is a search compromised by uncertainties, just like the search for UAP. But if some of the UAP are of extraterrestrial origin, the implications would be far greater for society than proving that dark matter is weakly interacting massive particles (WIMPs) as opposed to something else. The extraterrestrial finding may well change the way we perceive our place in the universe, our aspirations for space, our theological and philosophical beliefs, and even the way we treat other humans.

And all of these implications can be triggered by a single megapixel image obtained at a reasonable cost. In a forum that I attended recently concerning my book *Extraterrestrial*, I was asked about the prior probability assigned to the possibility that the weird interstellar object ‘Oumuamua or UAP are extraterrestrial in origin. I clarified that it is unknown just as in the case of dark matter being WIMPs. But because a megapixel image of UAP is affordable and is of great interest to the public and the government, we should simply obtain one. Indeed, a picture of an ‘Oumuamua-like object would be worth 66,000 words—the number of words in my book. We should not seek data from government-owned sensors that were not designed for this purpose but instead collect our own state-of-the-art scientific data in a reproducible fashion. Most of the sky above us is not classified.

In a podcast interview I recently had with a young audience, they agreed: “Let's just do it.” It was refreshing to see eye-to-eye with the torch bearers of the future, as well as with potential funders of the UAP imaging project, all within the same week. A day later I was asked by Rahel Solomon of CNBC: “How do you plan to celebrate UAP Day?” Thankful for the reminder, I said: “We will probably need our computers to figure out the nature of UAP, and so my plan is to celebrate the day with my computer.”

OPINION

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SPACE & PHYSICS

Learning to Live in Steven Weinberg's Pointless Universe

The late physicist's most infamous statement still beguiles scientists and vexes believers

Steven Weinberg, who died in July at the age of 88, was not only a Nobel laureate physicist but also one of the most eloquent science writers of the past half-century. His most famous (or perhaps infamous) statement can be found on the second-to-last page of his first popular book, *The First Three Minutes,* published in 1977. Having told the story of how our universe came into being with the big bang some 13.8 billion years ago and how it may end untold billions of years in the future, he concludes that whatever the universe is about, it sure as heck isn't about us. "The more the universe seems comprehensible," he wrote, "the more it also seems pointless."

For thousands of years, people had assumed just the opposite. Our ancestors gazed at the world around us—the people and animals, the mountains and seas, the sun, moon and stars—and saw the divine. As the 19th Psalm puts it: "The heavens declare the glory of God, and the firmament shows his handiwork." Even Isaac Newton saw a universe filled with purpose. In his masterwork, the *Principia*, he wrote: "This most beautiful system of the sun, planets, and comets, could only proceed from the counsel and dominion of an intelligent and powerful being."

Science advanced by leaps and bounds in the centuries following Newton, and scientists dialed back much of the God-talk. Many thinkers suggested that the universe runs like a mighty clockwork. Perhaps a creator was needed at the very beginning, to set it going, but surely it now runs on its own. Albert Einstein, who often spoke of God metaphorically, took a different tack. He rejected a personal deity but saw a kind of pantheism—roughly, the identification of God with nature—as plausible.

In the second half of the 20th century, many saw even these lesser gods as redundant. In *A Brief History of Time* (1988), Stephen Hawking speculated on the possibility that the universe had no precise beginning; his controversial "no-boundary proposal" (formulated in the 1980s with Jim Hartle) suggested that time might have behaved like space in the universe's earliest moments. Without a "time zero," there was no moment of creation—and nothing for a creator to

Bob Daemmrich *Alamy*

do. (It's hardly a surprise that some people who balk at the teaching of evolution also object to the teaching of big bang cosmology.)

Hawking's materialist philosophy, shared by Weinberg and many other prominent physicists,

sees the universe as arising through some combination of chance and natural law. Where Prince Hamlet saw purpose in even the minutest occurrence—"There's a special providence in the fall of a sparrow"—many of today's scientists see only the impersonal laws of physics.

When I interviewed Weinberg in 2009, he told me about the long shadow cast by that one sentence on a "pointless" universe. "I get a number of negative reactions to that statement," he said. "Sometimes they take the form, 'Well, why did you think it would have a point?' Other times people say, 'Well, this is outside the province of science, to decide whether it has a point or not.' I agree with that. I don't think that science can decide that there is no point, but it can certainly testify that it has failed to find one." And he specifically criticized what used to be called "natural theology"—the idea that, as the 19th Psalm suggests, one could learn about God by studying nature. Natural theology "is now discredited; we don't see the hand of God in nature. What conclusions you draw from that is up to you."

Although he never tried to hide his atheism—perhaps only Richard Dawkins and Sam Harris have been more vocal—Weinberg was sympathetic to those who yearn for a more intimate conception of God. "I think a world governed by a creator who is concerned with human beings is in many ways much more attractive than the impersonal world governed by laws of nature that have to be stated mathematically—laws that have nothing in them that indicates any special connection with human life," he told me. To embrace science is to face the hardships of life—and death—without such comfort. "We're going to die, and our loved ones are going to die, and it would be very nice to believe that that was not the end and that we would live beyond the grave and meet those we love again," he said. "Living without God is not that easy. And I feel the appeal of religion in that sense."

And religion deserves credit for giving us "requiem masses, Gothic cathedrals, wonderful poetry. And we don't have to give that up; we can still enjoy those things, as I do. But I think I would enjoy it more if I thought it was really about something, and I don't. It's just beautiful poetry, and beautiful buildings, and beautiful music—but it's not about anything."

The philosophy that Weinberg laid out in *The First Three Minutes* is now echoed in many popular physics books. In *The Big Picture* (2016), physicist Sean Carroll sees nothing to fear in an amoral universe. Our task, he writes, is "to make peace with a universe that doesn't care what we do, and take pride in the fact that we care anyway." In a similar vein, string theorist Brian Greene is adamant that it's physics all the way down. In *Until the End of Time* (2020), he writes: "Particles and fields. Physical laws and initial conditions. To the depth of reality we have so far plumbed, there is no evidence for anything else."

As for meaning, he is firmly in the Weinberg camp: "During our brief moment in the sun, we are tasked with the noble charge of finding our own meaning." In *The End of Everything* (2020), astrophysicist Katie Mack relays the existential opinions of an array of astronomers and physicists, most of whom repeat some version of the Weinberg-Carroll-Greene position: The universe doesn't come laden with meaning; instead you have to find your own. On the second-to-last page—clearly, this is where such things go—she reflects on "this great experiment of existence. It's the journey, I repeat to myself. It's the journey."

Weinberg saw science and religion as having nothing constructive to say to each other, a view shared by many (though certainly not all) of his colleagues. But the history of science could have unfolded differently. We can imagine generations of scientists standing with Newton, investigating nature as a path to understanding the mind of God. To be sure, some scientists think of their work in this way even today. (Guy Consolmagno, a Vatican astronomer, would be one example.)

But they are a minority. As science and religion began to go their separate ways—a process that accelerated with the work of Darwin—science became secular. "The elimination of God-talk from scientific discourse," writes historian Jon Roberts, "constitutes the defining feature of modern science." Weinberg would have agreed. As he told an audience in 1999: "One of the great achievements of science has been, if not to make it impossible for intelligent people to be religious, then at least to make it possible for them not to be religious. We should not retreat from that accomplishment."

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